DISSERTATION

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Social Capital, Technology Diffusion and Sustainable Growth in the Developing World

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Published 2000 by RAND
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Abstract

One of the topics that has emerged during the last decade in the policy agenda of national governments and international organizations is the design of policies that seek long-term economic growth *while* improving and sustaining the environment. The analysis of this type of policies is usually based on macroeconomic models which link changes in policy instruments (e.g., fiscal policy, pollution taxes, carbon permits, energy subsidies) to some outcome measure such as aggregate output or consumption. Critical assumptions within these models are related to the dynamics of technology-related-variables, such as total factor productivity, or the carbon intensity of the economy. Usually, these dynamics are defined exogenously, or endogenized by formalizing the effects of changes in input prices or R&D investments. Nonetheless, the micro-process of technology adoption, where decentralized heterogeneous economic agents interact and share information about the dynamics of the economy and the characteristics of new technologies, has been always ignored. Yet, it is this process which is behind the diffusion of new technologies and ultimately the dynamics of macro variables such as the carbon intensity of the economy.

Ignoring social interactions and learning is understandable in order to keep macroeconomic models manageable. If modeling these process does not contribute significantly to a better representation of the economy, there is not justification to bear the cost of building and simulating more complicated models. In this research I show, however, that social interactions are the source of externalities that when ignored may generate policy recommendations which are seriously biased. The social cost of this bias may well justify adding another layer of complexity to our current models. Hence, I develop an agent-based macro-econometric model for the developing world that endogenizes the process of technology diffusion by formalizing the role of social interactions. In this model, macro-behavior emerges from microeconomic decisions made by decentralized heterogeneous agents who are organized in networks. These networks influence agents information flows, their expectations about the dynamics of the economic environment, and ultimately their technology adoption decisions. The model is used to address the question of how to allocate aggregate income to the creation of human and produced capital, and how to distribute over time the consumption of natural resources and environmental services, in order to generate a sustainable growth path that maximize inter-temporal social welfare.

The research is organized in 7 Chapters. Chapter 1 reviews policy issues related to sustainable development and outlines the constraints imposed by current analytical frameworks. Chapter 2 is concerned with the definition and measurement of a sustainable growth path. In this Chapter I also implement an econometric analysis to measure the effects of social capital on the depletion rate of a given economy. Chapter 3 develops a macroeconomic framework that relates macroeconomic policies, technology policies, and environmental policies to indicators of sustainable development. Chapter 4 develops a theory of the linkage between social capital and technology diffusion. The insights are used in Chapter 5 to construct and calibrate the agent-based model of technology diffusion and growth. Chapter 6 uses the model to answer the question of how to allocate over time investments in produce capital, technology incentives and the consumption of carbon emissions. Finally Chapter 7 summarizes the major methodological and policy insights from the research.

Acknowledgments

This research is especially dedicated to my son, Juan David Robalino. Each page I have written represents time spent away from him. Without his understanding and patience I could have never completed the journey.

Many people have supported my work directly or indirectly. Among them my parents, who fostered my intellectual curiosity. My fiancée Isabelle who read many times each page of this document; she has been an oasis amidst a sometimes deserted research landscape. My colleagues and friends John Peabody, Jorge Muñoz, Leo Morales, and David Persselin, who helped me not only with parts of the research but also with parts of my life. The members of my committee: Robert Lempert, James Hosek and James Dewar who guided the work with patience. I am particularly grateful to Rob who encouraged my interest in complex adaptive systems. This research could have never been possible without his support. I also want to thank Scott Page, John Miller, and the people from the Sante Fe Institute who read my work and provided stimulating comments.

Of course, research also needs material support. I gratefully acknowledge financial support received from the RAND Graduate School through Dean Robert Klitgaard, the National Science Foundation, and the US Department of Energy. Also thanks to Evolving Logic for providing part of the hardware and software infrastructure required to simulate the models that support the research.

Finally, thanks to the Pacific Ocean and the sun for the colors at the end of each day.

Bangkok
February 2000

Chapter 1 - General Overview

1. Motivations and Research Objectives

How do we meet present needs without sacrificing the ability of future generations to satisfy their needs? This is the central policy question in the debate about sustainable economic development. This debate is directly related to the potential existence of an inter-temporal trade-off between economic growth and environmental degradation. Hence, one of the important topics that has emerged during the last decade in the policy agenda of national governments and international organizations is the design of policies that seek long-term economic growth that creates jobs and distributes income, while improving and sustaining the environment.

The diffusion of new production technologies with high productivity and low environmental damages will certainly play an important role in determining convergence to sustainable growth paths. Unfortunately, our understanding of the factors that affect the diffusion of these technologies is still limited. The majority of macro-models[1] used by the international assessment community to evaluate different dimensions of sustainable growth have treated technological progress exogeneously; those attempts to endogenize technological change have usually left out the process of technology diffusion. Recent efforts to model diffusion (see Messner, 1997; Goulder and Matai, 1997; Meijers, 1994; and Grübler and Gritsevskii, 1998), focus on the supply side of the process, that is learning by doing and uncertainty regarding the potential for costs reductions. Less has been done, however, in terms of the demand side of the process; in particular, the role of the quality and quantity of information that potential adopters receive via social interactions. Yet, empirical studies have shown that in the developing world, an important factor explaining the probability of adoption of new technologies is the size of the social network of potential adopters (see Bohane et al., 1999). These studies suggest that the process of learning via social interactions is the fundamental driver of the diffusion of new technologies in

the developing world, and the fundamental source of uncertainty. Therefore, there seems to be an intimate linkage between levels of social capital and technology diffusion. Social capital has been defined as the set of social networks, norms and institutions within an economy that shape agents' interactions (see Coleman, 1988; North, 1990; and Putnam, 1993). Within this broad definition of social capital, my focus is on its structural components: the density and quality of social networks. These networks are important for the process of technology diffusion because they affect the quality and density of information flows within the economy as well as the level of knowledge spillovers associated with the adoption of new technologies. Hence, the structural dimension of social capital affects the process through which economic agents generate expectations about the dynamics of different dimensions of the economy (e.g., the cost and performance of new technologies), as well as the transaction and operating costs related to the adoption of new technologies. Moreover, social interactions are sources of externalities that may deviate diffusion from social optimal paths. Countries with similar endowments of technological structures, human, natural, and produced capital, are likely to display very different development dynamics depending on the structure of their internal networks.

A first objective of this research is to analyze how social capital affects sustainability at the macro level. To do this, I study the dynamics of depletion rates in the developing world. The depletion rate of an economy is the value of natural resources and environmental services (NRES) that need to be consumed in order to generate one unit of Gross Domestic Product (GDP). This type of aggregate environmental indicator is necessary for evaluating and planning at the national level, and its role is similar to aggregate economic indicators (e.g., Gross Domestic Product) or social indicators (e.g., Life Expectancy). For my analysis, I use a panel data set for developing countries that, in addition to standard macroeconomic and social indicators, incorporates environmental measures (i.e., depletion rates), as well as proxies for social capital (i.e., the Ethno-Linguistic-Fractionalization index).

The second objective of this research is to provide the reader with an overview of the spectrum of policy interventions that are used to promote

sustainable growth, and their linkages to technology policies. I do this by reviewing the theoretical and applied literature generated on the subject during the last fifty to sixty years.

The third objective of the research is to study how social network structures affect the optimal allocation of human, produced, and natural capital over time. Indeed, while several views about the meaning of sustainable growth have proliferated, there seems to be an agreement in that it is mostly about preserving productive capacity through an efficient inter-temporal allocation of production inputs (see Serageldin and Steer, 1994). Determining this efficient allocation is of course a highly complex problem, given that different types of natural resources (renewable, such as forest and fisheries; and non-renewable, such as minerals) and environmental services (i.e., clean air and ecological diversity) are involved. Each is affected by particular types of externalities or other market failures, and requires specific policy instruments and institutional frameworks. To reduce this complexity, my focus will be limited to three types of non-renewable natural resources: oil, natural gas, and carbon. These so-called fossil fuels represent eighty percent of the sources of energy in the developing world. Countries exploiting these natural resources face two types of concerns: i) first, there is a concern regarding sustainability: what would happen if the natural resource is fully depleted?; ii) second, there is a concern with environmental damages associated for example with carbon emissions and extraction. The question that emerges is how to consume fossil fuels efficiently over time, given uncertainty regarding the diffusion of new production technologies that will affect not only capital and labor productivity, but also the degree of dependency of the economy on this type of natural resources. To answer this question, I develop and calibrate a multi-agent macro-econometric model for the developing world. The model emphasizes the role of social capital in agents' expectations formation, transaction costs, and technology choices.

There are three hypotheses driving this research. The first hypothesis is that, as development takes place, countries do not necessarily converge to a sustainable growth path that stabilizes depletion rates. Rather, multiple equilibria that result from different initial conditions and vagaries of history are likely to exist. The second hypothesis is that, due to network

externalities in the technology diffusion process, macroeconomic stability and sound environmental policy will not be sufficient to guarantee convergence to a sustainable path. Government interventions at the microeconomic level, through technology incentives, will often be a necessary condition. The third hypothesis is that policy choices ought to be sensitive to network structures. This is to say that there is not a universal set of policy recipes that countries should apply to increase their chance to converge to a sustainable path. Moreover, policies that operate efficiently under some given network structures can be worse than the status quo in others.

The remainder of this chapter is organized in two sections. The goal of Section 2 is to provide the reader with an idea of what is the magnitude of the challenge faced by developing countries in terms of sustainable growth. To do this, I review some basic economic, social and environmental indicators for several developing and developed countries. I also discuss the main features of the "dominant" view regarding the strategy to promote sustainable development in large. Section 3 discusses briefly the methods used in the research to measure the determinants of depletion rates, and to determine optimal schedules for the consumption of fossil fuels. While these methods are developed extensively in subsequent chapters, this section allows the reader to have a general idea of "where we are going" and "how we are getting there".

2. Background: Problems and Strategies

2.1 The Challenge of Sustainable Development

While propositions about what is meant by sustainable development have proliferated, there is a general consensus that it is mostly about increasing standards of living of current generations, while preserving productive capacity for future generations. Alternative definitions and my own are discussed extensively in Chapter 2. Here, I limit myself to give the reader a flavor of the enormous challenge facing developing countries to increase the standards of living of their population while preserving resources for future

generations. While several economic, social and environmental indicators could serve this purpose, three of them are particular compelling when used together: consumption per capita, distribution of income, and depletion rates.

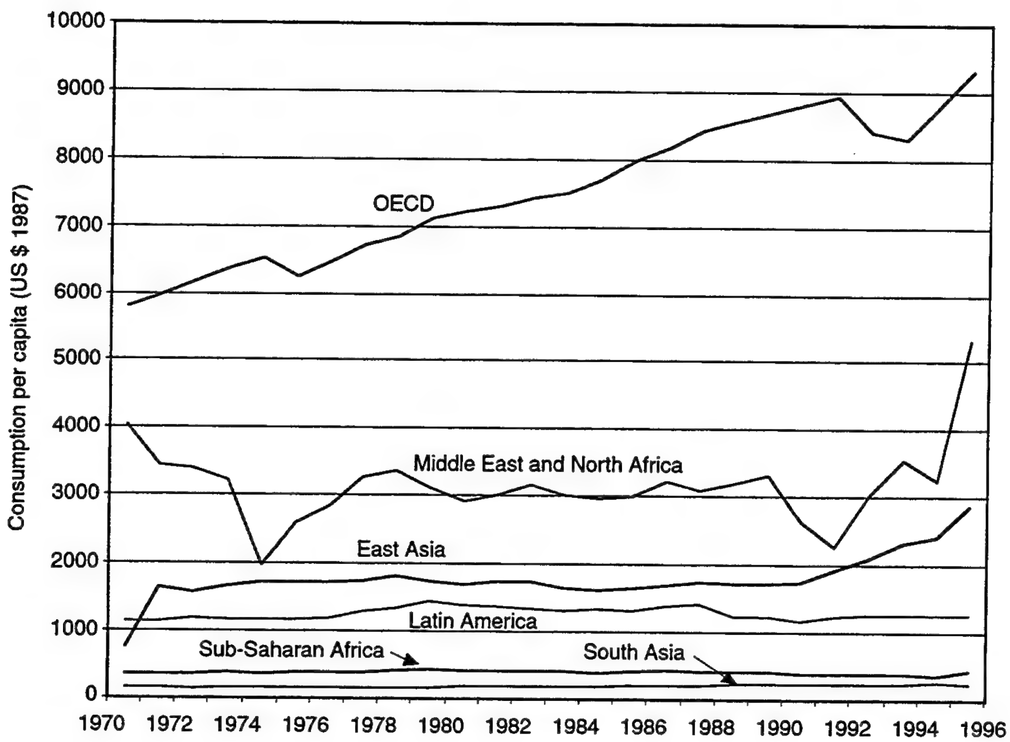

Figure 1.1: Dynamics of Consumption Per Capita.

Source: Author calculations based on World Bank data.

World consumption per capita is displayed in Figure 1.1 for six regions of the world. The disparities are striking. While in OECD countries consumption per capita has been rising steadily reaching a level of more than USD (1987) 9,000 in 1995, in regions such as Sub-Saharan Africa and South Asia, consumption per capita has stagnated and has remained well below USD (1987) 1,000 per year.

During the last decade, consumption per capita has been rising in the Middle East and North Africa as well as East Asia. However, high inequalities persist among the countries within these regions. Indeed, a few countries such as Kuwait in the Middle East region, and Singapore and Hong Kong in Asia are the main drivers of this increase.

This situation is complicated by the fact that income in developing countries is highly concentrated. This implies that a majority of the population does not even get the USD 2,000 or so that they would get if we distributed income equally. A quick glance at the Gini coefficient, our proxy for income distribution, gives an idea of the problem (see Figure 1.2). High values of the Gini coefficient indicate a more concentrated, less equal distribution of income. Income tends to be more concentrated in Latin America, Africa and the Middle East and not surprisingly less concentrated in Eastern Europe countries. However, in the latter, there has been a tendency to concentrate income during the past two decades - an inevitable consequence of market reforms. In the other regions of the world, OECD and Asia, the distribution of income has remained roughly constant. Income redistribution may be as important a policy as growth promotion, particularly in regions such as Latin America, Africa and the Middle East. Indeed, with levels of consumption per capita close to USD (1987) 1,000, a highly concentrated distribution of income implies that broad segments of the population are struggling to satisfy basic needs. In 1997, the share of the world population living under the poverty line was estimated to be close to 40% (see United Nations Development Program, 1998). Even in Asia, where both the consumption per capita indicator and the Gini coefficient indicator show a more positive scenario, the number of households living under the poverty line has tripled as a result of the recent financial crisis. Of the 4.4 billion people in developing countries, nearly three fifths lack access to safe sewers, one third have no access to clean water, one quarter do not have adequate housing, and one fifth have no access to modern health services of any kind (see United Nations Development Program, 1998)[2].

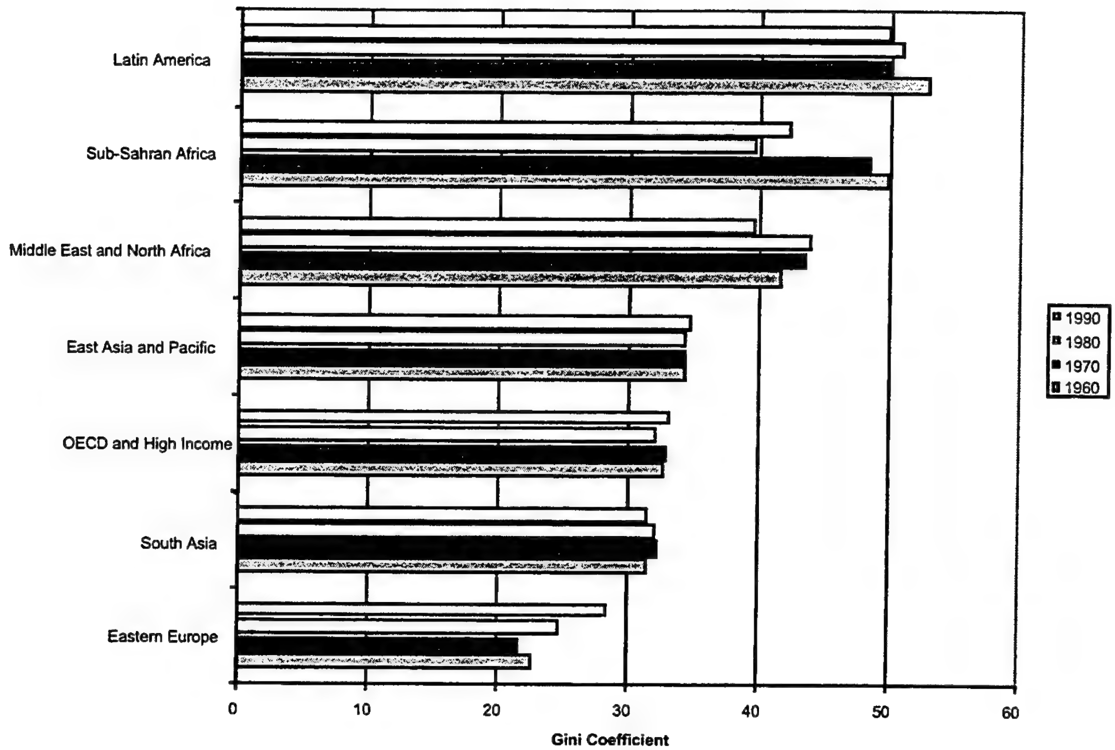

Figure 1.2: Income Distribution in the World.

Source: Deininger and Squire (1998).

The message from Figures 1.1 and 1.2 is simple: the challenge of increasing consumption per capita in the developing world to the levels of developed countries is overwhelming. As an illustration, for the average Latin America country to raise consumption per capita from close to USD (1987) 1,000 to USD (1987) 10,000 in less than 20 years, it would need to grow at approximately 12% per year. With growth rates of 2% per year, Latin America would need to wait one century.

The environment

Pressures to promote growth have often been accompanied by an irresponsible management of natural resources. To measure the environmental intensity (i.e., the rate of use of the environment in national production) of the economy, I have computed depletion rates on the basis of World Bank data (see Chapter 2 for a description of the data). These depletion rates are defined as the value of natural resources consumed per unit of GDP. By far, the dependence of developing countries on their natural resource base has been

higher than in developed countries. While the depletion rates are close to 5% of GDP in OECD countries, this number fluctuates between 15% and 35% in developing countries (see Figure 1.3). The stock of natural capital is depleted by the action of two factors: pollution emissions and consumption of natural resources. While current measurements of the economic costs of these two factors are necessarily only an approximation (see Chapter 2 for a discussion), they provide an idea of the magnitude of the problem.

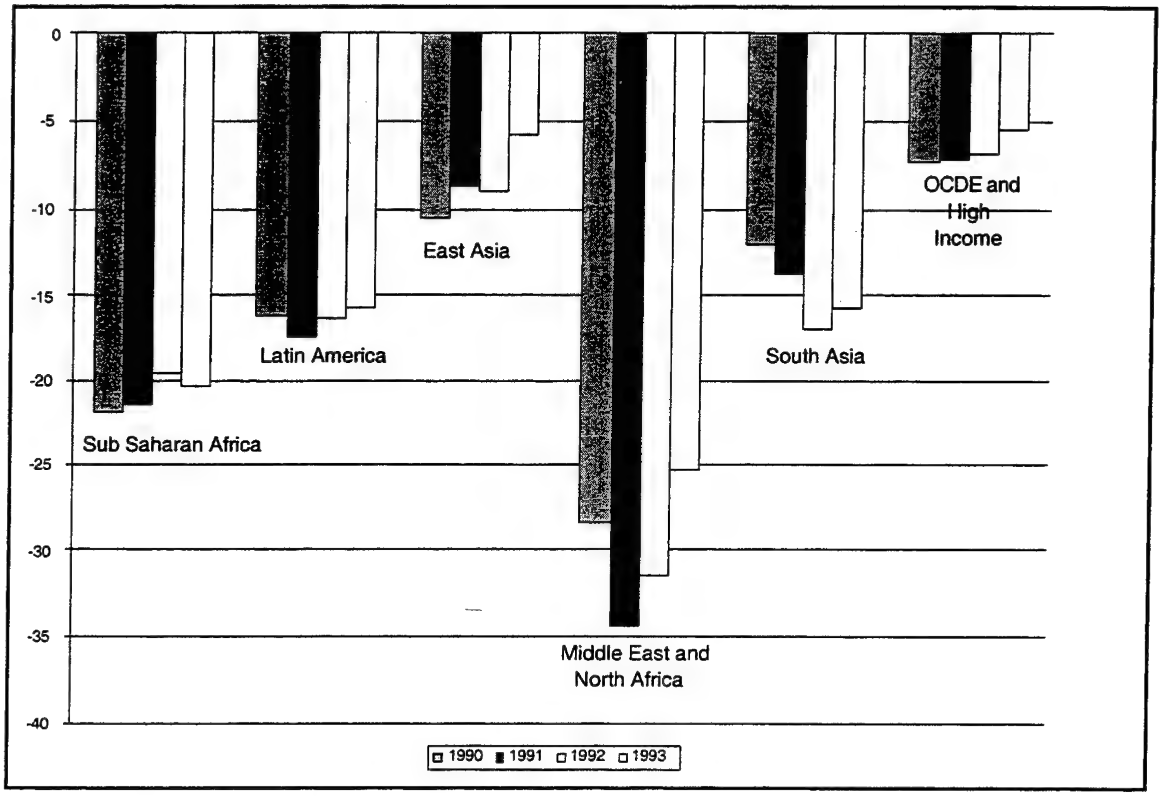

Figure 1.3: Depletion Rates in the World (% of GDP).

Source: Author calculations based on World Bank data.

To illustrate the impacts that current depletion rates may have on the dynamics of the stock of natural capital, I have conducted some simple forecasts. On the basis of information on natural capital per capita, I have computed total stock of natural resources for each of the different regions of the world for the year 1995. I have also approximated total GDP by region. Then, for various growth rates of total GDP, I have computed the number of years that would be required to observe full depletion of natural capital

under two assumptions: a) that the current stock does not increase, and b) that current depletion rates remain constant. The results are summarized in Table 1.1.

	Natural Capital/ GDP ratio	Depletion Rate (%GDP)	Sustainable depletion Rate (assuming 1% replenishment rate)	Max.level of GDP/ current GDP	Years before full depletion g=0.5%	Years before full depletion g=2%	Years before full depletion g=5%	Years before full depletion g=10%
OECD and High Income	0.92	0.05	0.0092	18.4	584.5	147.2	59.7	30.6
Latin America	4.86	0.15	0.0486	32.4	697.4	175.6	71.3	36.5
East Asia	0.72	0.05	0.0072	14.5	535.9	135.0	54.8	28.0
South Asia	18.68	0.15	0.1868	124.5	967.3	243.6	98.9	50.6
Middle East and North Africa	4.40	0.25	0.044	17.6	575.2	144.9	58.8	30.1
Sub-Saharan Africa	18.86	0.2	0.1886	94.3	911.6	229.6	93.2	47.7

Table 1.1: Projected Depletion Rates.

Source: Author calculations.

The third column in Table 1.1 gives the sustainable depletion rate, computed under the assumption of a 1% replenishment rate for the stock of natural resources[3] (a highly optimistic assumption in the case of the aggregated stock, see Chapter 2). We observe that for the majority of regions (including OECD countries) the sustainable depletion rate is lower than the current depletion rate. The fourth column in Table 1.1 shows the maximum level of GDP that can be supported with the current level of natural capital. This column is computed by dividing the natural capital/GDP ratio by the depletion rate. Hence, in the case of OECD countries, the current stock of capital could finance a level of GDP 18.4 times higher than the one currently observed. In the case of South Asia, the current stock of natural capital is sufficient to increase current GDP 124.5 times. The last four columns of the table simply indicate how many years would be required for a given region to attain this maximum level of GDP under different growth rates. For very small rates (0.5%

per year), the current stock of capital will last for more than five centuries. However, for growth rates higher than 5% per year, full depletion of natural capital may be expected within the next century. The most sensitive regions are East Asia, the Middle East and OECD countries (although in the latter there is no pressure to increase growth rates above 2%). The scenarios depicted in Table 1.1 are of course extreme, because I rule out technological progress and factors substitution. Nonetheless, the results provide an idea of the magnitude of the tradeoffs involved between growth and the stock of natural resources, and the need to reduce depletion rates in order to generate sustainability.

2.2 General Strategies

Porter and Christensen (1999a) summarizes what I think is the mainstream view regarding a general strategy to promote sustainable economic development:

"Economic development seeks to achieve long term sustainable improvement in a nation's standard of living, adjusted for purchasing power parity. Standard of living is determined by the productivity of a nations' economy, which is measured by the value of the goods and services produced per units of the nations' human, capital and physical resources [...] Other things contribute to standard of living besides wages and return to capital such as income inequality and environmental quality. The macroeconomic and political underpinnings of competitiveness and economic development are becoming better understood. A stable political environment and sound political and legal institutions represent important preconditions [...] A macroeconomic policy involving prudent government finances, a manageable debt, a moderate cost of government, a limited government role in the economy and openness to international markets promotes national prosperity. In addition, growth theory stresses the importance of a high rate of aggregate national investment in human and physical capital."

Porter and Christensen (1999b), however, also argues that while macroeconomic policies are necessary, they are not sufficient.

"[...] As important - or even more so - are the microeconomic foundations of economic development, rooted in firm operating practices and strategies as well as in the business inputs, infrastructure, institutions and policies that constitute the environment in which a nations' firms operate [...] Some economists think that if the proper macroeconomic

conditions can be put in place, the rest will take care of itself. If governments operate efficiently, aggregate savings are ample and inflation is controlled, the lower interest rates will lead firms to make the investments necessary to enhance competitiveness. If government resources are allocated to education, the resulting rise in human capital will translate into jobs with higher wages. If government removes distortion in prices and exchange rates, firms will become more innovative and sophisticated. There is some truth in that, because lowering the cost of capital, raising the rate of investment and removing distortions certainly matter. However, the gap between macroeconomic policies and company competitiveness is a wide one. A myriad of intervening circumstances at the microeconomic level must be understood and addressed by the private sector and through government policies if a nations' prosperity is to improve."

In this research, I will focus on one of these microeconomic issues: the process of technology diffusion. Hence, I am going to abstract many of the things that are important to promote sustainable development to focus on the fundamental issues behind sustainability: how to create an appropriate portfolio of human, produced, and natural capital that is able to preserve productive capacity over the long run, and how to hedge this portfolio with appropriate technology policies. Indeed, I argue that it is ultimately the adoption of new processes and technologies that affect firms' productivity and the type of interactions existing between the economy and the environment. The story that I will be telling is somehow similar to that of Robert Solow (see Solow, 1999). Suppose we adopt a simplified picture of an economy living in some kind of long run. That is, we ignore short run fluctuations resulting from business cycle problems connected with unemployment and excess capacity, or overheating and inflation. Let's further assume that the economy has a fixed stock of non-renewable natural resources that are essential to production, but that can be substituted to some degree by other resources: human and produced capital. Substitution is important, and as stated by Solow, without this minimal degree of optimism, sustainable growth is not an issue. Indeed, the only choice is between a "short happy life" and a "longer unhappy one". In this economy, the welfare of individuals depends on how much has been produced by using the total human and produced capital, and depleting some of the natural resource base. Hence, we can imagine that each year there are three types of decisions to be made: a) how much to invest and how much to consume; b) how to distribute the investment between human and produced

capital; and c) how much of the remaining stock of natural resources to use. The use of these "irreplaceable resources" implies that future generations will have less of them, but at the same time will inherit a higher stock of human and produced capital.

My focus will not be on the full stock of natural resources, but only on the stock of fossil fuels. Hence I will analyze the question of how should developing countries distribute over time the "consumption" of carbon emissions, in order to promote sustainable growth, and how this consumption should be coordinated with investments in produced capital and new technologies. Nonetheless, the methods that I develop can be expanded to include other types of natural resources.

2.3 The Need for an Alternative Analytical Framework

There are two major difficulties in addressing the question of how technology incentives and investments in alternative forms of capital should be coordinated over time to increase the likelihood of an economy converging to a sustainable path. The first difficulty is related to measurement. Too often, the debate about sustainable growth has been limited to expressing emotions regarding the environment, without attempting to measure the impacts of alternative growth paths or their policy requirements. For the first time, however, a comprehensive database on the wealth of nations and its dynamics is available. The information is still in a very aggregated form, and current measures are necessarily imperfect. Nonetheless, they allow researchers to think about sustainable growth in a more rigorous way. In the context of this research, the database is used to study the determinants of the dynamics of depletion rates, and to calibrate the simulation model of growth used to locate sustainable growth paths.

The second difficulty has to do with the incorporation of the process of technology diffusion within the simulation model. Currently, the international assessment community is lacking an adequate framework for the analysis of the use of technology policies to promote sustainable growth (see

Kemp et al., 1994). Indeed, the current macroeconomic models that are used to analyze the impacts of environmental, fiscal and monetary policies on the economy treat technological progress exogenously. Moreover, modern models are constructed and simulated under the assumption of rational expectations, implying that economic agents not only know the model used to represent the economy, but also the expected behavior of the government and other agents. This practice is surprising since there are empirical and theoretical studies showing that expectations do not necessarily converge to the perfect rationality equilibrium (see Grandmont, 1998a). Furthermore, radical uncertainty - ignorance about the probability distribution of the random variables - is pervasive in the technology diffusion process (see Dosi, 1988).

The process of technology diffusion is studied extensively in Chapter 3. A general conclusion is that adoption decisions depend on three factors: a) firms' characteristics and preferences; b) firms' knowledge about available technology and process; and c) expected costs and benefits. The complication is that knowledge and expectations are influenced by several factors at the macro and micro levels. At the macro level, the dynamics of prices and wages are crucial. At the micro level, important elements include demand conditions, related and supporting industries, local rivalry, and information infrastructure. This is to say that the way firms are organized, how they share information, and how their costs functions are interrelated, are essential features of the diffusion potential of new technologies. In this research, I study firms' interactions through the concept of social networks. Three features of these networks are particularly important and receive most of my attention: a) their density; b) the strength of their links; and c) the type of behavior they promote - competitive or cooperative behavior. These networks affect the quantity and quality of information flows, but are also the source of social spillovers that very often lead to coordination failures (see Chapters 3 and 4 for a discussion). Hence, I combine three analytical innovations: a) an agent-based model of technology diffusion that formalizes the role of social interactions; b) a macroeconomic model of growth that incorporates an environmental component; and c) exploratory modeling: a methodology for policy analysis under extreme uncertainty. Each of these instruments is described briefly in the next section.

3. Methods

3.1 Econometric Analysis

I have compiled a database that combines standard economic indicators with environmental, institutional, and social indicators for several countries and different years. The data comes from four main sources: World Bank Tables (see World Bank, 1998b), Sachs and Warner (1995), Levine and Renelt (1992), and the World Bank measures of national wealth and genuine savings (see Dixon et al., 1998). The main purpose of this panel data is to explore what are the main structural determinants of observed depletion rates in the developing world and what is the role of social capital and institutions. I then test two hypotheses: a) depletion rates are closely related to the level of economic development, so that an invisible hand will reduce depletion rates as countries enter the developed world (the Kuznets hypothesis); or b) countries do not necessarily converge, and rather form depletion rate clusters similar to the economic growth clusters explored by Quah (1996).

3.2 The Agent-Based Model of Technology Diffusion and Social Interactions

The use of agent-based models in the social sciences is becoming more and more popular not only for theoretical studies but also empirical ones (see Epstein and Axtell, 1997; and Wildberger et al., 1999). There are at least two reasons for this trend. First, as social sciences evolve, more and more researchers realize the pressing need to incorporate in policy analysis a more realistic representation of social interactions, heterogeneity and learning. The second reason is that rapidly increasing computational power coupled with low computational costs is able to satisfy the high demand for computational resources of agent-based models. In this research, I use this type of modeling technique to endogenize the process of technology diffusion, and therefore the dynamics of labor productivity and the fossil fuels intensity of the economy. The model that I use is an extension of the technology diffusion model used in the work on climate change policy (see Robalino and Lempert,

1999). I formalize the behavior of a sample of heterogeneous producers who are organized in networks. Producers (i.e., firms) make technology choices on the basis of expectations about the macroeconomic environment and the cost and performance of alternative technologies[4]. Their networks affect the flows of information and therefore the dynamics of their expectations, but also the costs of adoption and operation of these technologies. These networks then become a proxy for "social capital" and are the source of the diffusion externalities discussed in the previous section. Usually, productivity growth rates and fossil fuels intensity are modeled as time series that incorporate some stochastic process (see Pizer, 1999). The agent-based model of technology diffusion can be viewed simply as a more complex statistical process resulting from simulated interactions within a network of potential adopters of new technologies. Like any time series equation, the network can be calibrated to reproduce statistical processes that are consistent with observed data.

In order to make the model useful for policy analysis, networks, technologies, and agents' parameters need to be chosen in a way that the model generates dynamics that are consistent with known data. I use four data constraints: past growth rates of GDP, labor productivity, depletion rates, and diffusion rates for major technologies. Using moment simulation methods (see Dowlatabi and Oravetz, 1997) I locate a set of parameters that, for each of these four variables, generates means and variances consistent with the empirical observations.

The model of technology diffusion and the calibration method are extensively described in Chapter 5. The model is used to compute the distribution of production technologies within the economy, the total level of output, the demand for alternative types of labor, and the demand of natural resources. These variables are then passed to the macroeconomic model of growth that computes equilibrium prices, domestic absorption, and external accounts. This latter model is described briefly in the next section.

3.3 General Equilibrium Macroeconometric Model for the Developing World

I use an expanded version of the Huaque, Lahiri, and Montiel (1993) one-sector macroeconomic model for the developing world (see Chapter 5 for a complete description of the model). The model has been modified to incorporate an environmental module that keeps track of the stock of natural resources. This stock is affected by the demand for natural resources and environmental services, that depend on technology choices and are computed by the model of technology diffusion. The core HLM model is used to compute prices (consumers prices, interest rates, and wages), domestic absorption, and the balance of payments. The core model passes these variables to the model of technology diffusion, and obtains in return information on the total level of output and factor demands.

For the parameters of the behavioral equations of the HLM model (e.g., consumption and investment) I have preserved the original estimates of the authors for the developing world. Given that my focus is on technology diffusion, I do not attempt to explore other combinations of these parameters.

3.4 Decisions under Uncertainty and Exploratory Modeling

The analysis of policies related to the dynamics of the technological factor is usually associated with high levels of uncertainty. Hence, policy choices become dependent on particular parameters and yet ignore the underlying probability distribution of those parameters. In these cases, exploratory modeling methods (see Bankes, 1993) provide a consistent mechanism to evaluate and design robust policy interventions. The general methodology consist of 6 interrelated steps:

1. Identification of a set of model parameters consistent with known data through simulation estimation methods;
2. Study of the effects of the parameters on the dynamics of the model through the use of search algorithms and specialized simulation environments;

3. Delimitation of the regions of the parameter space associated with particular dynamics;
4. Design of adaptive decision strategies to implement policy objectives;
5. Simulation of the strategies in the different regions of the uncertainty space; and
6. Search for robust strategies under different assumptions regarding the probability of observing alternative regions of the uncertainty space.

Here, I use some of these methods to test the robustness of "optimal" policy interventions in specific regions of the policy space.

3.5 Dynamic Stochastic Optimization

With the models described in the previous sections, alternative types of economies can be represented on the basis of initial values for model parameters. I use a benchmark country to shed light on the question of how to allocate over time investments in produced capital, the "consumption" of carbon emissions, and technology incentives. There are several model parameters that will affect policy choices. For many of these parameters, we only know their probability distribution, while for others even this probably distribution is not well understood. Hence, as described in Chapter 6, I solve a stochastic dynamics optimization problem that integrates most of these uncertainties.

4. Dissertation Structure

The remainder of the dissertation is made of six chapters. Chapter 2 is concerned with the definition and measurement of sustainable growth. It develops and tests an econometric model that looks at the linkage between depletion rates, macroeconomic, social and institutional indicators, and economic growth. Chapter 3 is a theoretical chapter. It deals with the process of technology diffusion and its linkage with social capital. It reviews the literature on both of these concepts and introduces a set of mathematical tools, mostly from statistical mechanics, that prove useful for

the analysis of models with social interactions. Chapter 4 is concerned with a more in-depth discussion of the type of policies available to promote sustainable growth. Chapter 5 introduces the agent-based model of technology diffusion and the macroeconomic model of growth. Chapter 6 describes the methods and results of my computational experiments. Finally, Chapter 7 summarizes my main findings.

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[1] Modern versions of these models include CRA's "IIAM" (see Charles River Associates, 1998), OECD's "General Equilibrium Model of Trade and The Environment" (see Beghin et al., 1996), the World Bank's "Overlay Model" (see World Bank, 1998a), the IMF's "Multimod Mark III" (see Laxton et al., 1998), and RAND's "System Model for the Developing World" (see Bernstein et al., 1999).

[2] However, the benefits of redistributing income may go far beyond helping the poor. Indeed, less inequality tends to be associated with more economic growth through the access of a higher share of the population to capital markets and a reduction in taxes or welfare public expenditures (see Deininger and Squire, 1998). Also, there are at least three channels through which the distribution of income affects growth. First, as suggested by Chatterjee (1991) and Tsiddon (1992), a more unequal distribution of assets would imply that for any given level of per capita income, a greater number of people are credit-constrained (given that creditors face imperfect information and that this information is costly - see Stiglitz and Weiss, 1981). In economies where individuals make indivisible investments that need to be financed through borrowing, this would imply lower aggregate growth. A second channel – that we analyze intensively in this research – is the fact that investment possibilities are not only affected by individuals' stock of collateralizable assets, but also by neighborhood effects and social capital. Income and asset inequality in this context will be associated with low levels of social capital, that will potentially have high negative intertemporal effects through societies' ability to take advantage of exogenous technological opportunities (see Galor and Zeira, 1993). Finally, income inequality may affect growth through the political system (see Alesina and Roderick, 1994; Persson and Tabellini, 1994; and Bertola, 1993). Indeed, societies with more unequal distributions of income will be more prone to implement redistributive policies (taxes and government subsidies) that have negative impacts on economic growth.

[3] The depletion rate d for country i is given by: $d_i = n_i / Q_i$ where n is the consumption of natural resources and Q is GDP. The sustainable consumption is given by: $n_i^* = R.N_i$ where R is the regeneration rate and N is the stock of natural resources. It follows that the sustainable depletion rate is $d_i = R.\eta_i$ where η is the natural resources/GDP ratio given by: $\eta_i = N_i / Q_i$.

[4] Obviously, I cannot attempt to reproduce the dense set of production technologies and processes that exist within a given economy at a particular point in time. Rather, I work with an aggregate set of technologies that in some aspects is similar to the set of "capital vintages" used by modern macro-econometric models (see Beghin et al., 1996). The difference is that in my framework the pattern of adoption of these vintages is not defined exogenously.

Chapter 2 - Sustainable Development: Definitions, Measures and Determinants

1. Introduction

During the last decade, we have observed a remarkable upsurge of concern about the sustainability of economic development over the long run. As a result, considerable effort has been invested in the design of an analytical framework that can be used to think about policies that promote sustainable growth. This task has implied several methodological challenges, ranging from trying to define what is meant by sustainable development, to operationalizing the definition and designing indicators that can be used to monitor it.

This chapter has three objectives. The first is to introduce methodological issues about definitions and measurement of sustainable development. The second objective is to define a set of macro-flags that can be used to monitor sustainable development, and analyze their dynamics during the past two decades. The third objective is to better understand what are the factors that explain why some countries tend to make more intensive use of their natural resources base. This is a topic that has received little or no attention in the empirical literature, and yet is important for the assessment of sustainable growth.

The chapter is organized in five sections. Section 2 is concerned with definitions. Sections 3 and 4 are concerned with measurements. Finally, Section 5 is concerned with the empirical analysis of the dynamics of depletion rates.

2. What Do We Mean by Sustainable Development?

It is safe to state that there is not a single, commonly accepted concept of sustainable development, how to measure it, or even less on how it should be promoted. There are, in my opinion, two major views on the subject. On one hand, we have the ecologists' view that associates sustainability with the preservation of the status and function of ecological systems. On the other hand, we have economists that consider that sustainability is about the maintenance and improvement of human living standards. In the words of Robert Solow "if sustainability is anything more than a slogan or expression of emotion, it must amount to an injunction to preserve productive capacity for the indefinite future" (Solow, 1999). Hence, while in the ecologists' view natural resources have a value that goes beyond their productive use and cannot be substituted by other forms of capital, within the economics view natural resources can be consumed and substituted by other forms of capital, as long as productive capacity is maintained (see the discussion in Chapter 1, Section 2).

The World Commission on Environment and Development (Bruntland Commission) defined sustainable development as "development that meets the needs of the present without compromising the need of future generations to meet their own needs" (Bruntland Commission - see World Commission on Environment and Development, 1987). Toman (1999) better describes the reaction of both economists and ecologists to this definition:

"[...] If one accepts that there is some collective responsibility of stewardship owed to future generations, what kind of social capital needs to be intergenerationally transferred to meet that obligation? One view, to which many economists would be inclined, is that all resources - the natural endowment, physical capital, human knowledge and abilities - are relatively fungible sources of well being. Thus, large scale damages to ecosystems such as degradation of environmental quality, loss of species diversity, widespread deforestation or global warming are not intrinsically unacceptable from this point of view; the question is whether compensatory investments for future generations are possible and are undertaken. This suggest that if one is able to identify what are determinants of these "needs" and what types of resources are required to satisfy these needs, one should in principle determine

[which] resources to transfer. An alternative view embraced by many ecologists and some economists, is that such compensatory investments often are unfeasible as well as ethically indefensible. Physical laws are seen as limiting the extent to which other resources can be substituted for ecological degradation. Health ecosystems, including those that provide genetic diversity in relatively unmanaged environments, are seen as offering resilience against unexpected changes and preserving options for future generations."

One approach to bring the views of economists and ecologists together is to assume that individuals derive welfare from, and have preference for, consumption, environmental quality, and social health, thus ruling out perfect substitution. This being the case, it is plausible to postulate the existence of a social welfare function that incorporates indicators of consumption, environmental quality and social stability. Then a sustainable development path can be defined as the one that maximizes the present value of the inter-temporal social function (see Gillis et al., 1992). In other words, a given set of economic, environmental, and social indicators would be aggregated into a single indicator that becomes a universal measure of sustainability. Policies could then be evaluated with respect to the impacts that they have on the indicator. An example of this type of indicator is the Human Development Index (HDI, see United Nations Development Program, 1991). This indicator essentially represents the average of life expectancy, literacy, and income per capita, and is published annually in the Human Development Report (see United Nations Development Program, 1995). The HDI is often used by national governments and international organizations to set policy goals and allocate public resources (see Murray, 1993). This implies that indicators like the HDI, in principle a positive or descriptive indicator, become normative or prescriptive indicators. Then, implicitly, the indicator is reflecting *some* set of "preferences". But given the way that indicators are usually constructed, these preferences are not likely to be "social preferences". Hence, maximizing the HDI may not be as desirable as maximizing some other weighted measure of life expectancy, literacy, and income per capita. Even worse, there may be other dimensions, currently omitted, that individuals consider important and that should therefore be included in any indicator of sustainable development. One of these dimensions is certainly the environmental dimension.

Therefore, coming up with a social function that aggregates social preferences may be an impossible task. The existence of such a social function depends on strong assumptions regarding agents' preferences and functional forms (see Harsanyi, 1953; Arrow, 1963; Bailey et al., 1980; Atkinson, 1980; and Lambert, 1993), and as suggested by Goodin (1986) in most cases may not exist. But even if it does, how do we go about measuring its components? In an attempt to approximate what could be interpreted as a set of universal social values about an indicator of sustainable development, I conducted a simple e-mail survey. The survey asked questions about individuals' preferences for three dimensions of sustainable development: economic growth, environmental quality, and income redistribution. The summary of weights that individuals place on each of these three dimensions is summarized in Appendix 8.1. Although the sample of individuals is not representative of the population, the results illustrate the high variance in individual preferences and give an idea of how difficult it would be to come up with a consensus regarding what is the appropriate social function to assess sustainable development.

These results convinced me to abandon the use of a social welfare function and opt instead for a measure that could be more transparent, and enjoy almost universal acceptance. In his work on common values, Bok argues that a minimalist set of social values is needed for societies "to have some common ground for cross-cultural dialogue and for debate about how best to cope with military, environmental, and other hazards, that, themselves, do not stop at such boundaries" (see Bok, 1995). Common values are not simply the values of the majority. Rather, they are a set of minimal values that nearly everyone in a society recognizes as legitimate for their own, but that have never been universally applied in society. Minimal values constitute a set of values that can be agreed upon as a starting point for negotiation or action. They represent the "chief or more stable component" of what individuals can hold in common. As stated by Murray (1993) "if many individuals after deliberation hold a preference or value then this value should be considered seriously".

Serageldin and Steer (1994), and Toman (1999) suggested a set of common views about sustainable development. The idea is that sustainability is about preserving and enhancing the opportunities available to people in countries around the world, and that these opportunities depend on a nation's

accumulation of wealth. This wealth has three components: the stock of produced capital, the stock of natural capital, and the stock of human capital[1]. The main difference with this approach and Solow's is that a sustainable path needs not only to preserve productive capacity, but also access to a *minimum* level of environmental services and ecological diversity.

Within this framework, an indicator of sustainability is the *genuine savings* rate (see Section 4 for a discussion) of the economy given by:

$$s_t = \frac{GDP_t * (1-c_t) - K_t\delta_k + (N_t R - n_t) + h_t}{GDP_t}, \tag{2.1}$$

where c_t is the share of GDP that goes to consumption, $K_t\delta_k$ is the depreciation of the stock of produced capital during period t, n_t is the amount of natural resources and environmental services consumed during period t, R is the regeneration rate, and h are investments in human capital. As we discuss in the next section, data is now available to compute s_t.

On the basis of (2.1) I can provide a first (weak), definition of a sustainable growth path.

Definition 2.1: Weak sustainable growth path. I call weak sustainable growth path a path that converges to a state where s_t is non-negative.

This definition provides a heuristic to evaluate how well countries are preparing for the future. Along a sustainable path in the weak sense, the economy is generating enough resources to substitute for the depletion of natural resources. Hence, productive capacity is preserved. In other words, total wealth is constant or rising. If a country has a gross savings rate of 15% of GDP, a depreciation rate of 10%, a depletion rate of 10%, and no investment in human capital, it will be reducing its wealth by 5% per year (i.e., s_t=-0.05). This does not necessarily imply that the country is outside a sustainable path. Indeed, it may be the case that a high depletion rate is optimal during a given period of time, if stabilization follows. Nonetheless, a negative s_t can be interpreted as a *red flag*. This flag indicates that the

current growth strategy can not be maintained forever and that stabilization will be necessary.

In the absence of damages, full depletion of the natural resource base is not necessarily inconsistent with sustainability. However, in the presence of damages, intuitively, we can see that sustainability will require the stabilization of the stock of natural capital above the threshold δ_1.

A second, (strong), definition of a sustainable growth path acknowledges that there may be several paths that generate sustainability in the weak sense. Among these paths, however, there are those that generate a maximum level of consumption per capita. It is ultimately this consumption that is a proxy for standards of living or social welfare. Several functions can be used to measure the utility that individuals derive from consumption. Here, I use one that is common in macroeconomic studies (see Pizer, 1998). The function is given by:

$$U(C_t) = L_t \frac{(C_t / L_t)^{1-\tau}}{1-\tau}, \tag{2.2a}$$

where C is consumption, L represents population, and τ is the coefficient of risk aversion.

Definition 2.2: Strong sustainable growth path. Strong sustainable growth path is a path that maximizes the inter-temporal value function given by:

$$V(C_t) = \sum_t (1+r)^{T-t} \left\{ L_t \frac{(C_t / L_t)^{1-\tau}}{1-\tau} \right\}, \tag{2.2b}$$

where r is a discount rate and T is the end of the planning horizon. Maximizing consumption over the infinite time horizon implies that productive capacity needs to be preserved over that infinite time horizon. The optimal inter-temporal allocation of natural resources will be a necessary condition.

From these definitions, two caveats are worth noticing. First, by linking optimality exclusively to consumption per capita and stability of wealth per capita, we ignore several issues that are important in order to assess sustainability. These issues include, for example, the way income is distributed across individuals in a given society, or the level of access of different segments of the population to basic needs such as health and education. Nonetheless, the approach sets boundaries on a nation's possibilities to improve these standards of living.

A second caveat is that the definitions ignore other dimensions related to quality of life and social health, such as the utility that individuals derive from living in societies with low crime rates or strong political and civil rights. Unfortunately, the shortcut is necessary for simplicity and fundamentally to keep policy recommendations independent of functional and parametric choices. Still, by considering the stability of the stocks of natural, produced, and human capital the definitions acknowledge the importance of investments in education, health, and environmental protection. Furthermore, it has been extensively documented that measures of social health and quality of life are correlated with GDP per capita (see Klitgaard and Fedderke, 1995).

The next two sections of this chapter assess sustainability in the developing world on the basis of the weak definition. The last chapter of this research will be concerned with the strong definition.

3. Measuring the Wealth of Nations

To assess sustainability on the basis of our weak definitions, we need information on stocks and flows (i.e., investments or consumption) of produced, human, and natural capital. Measuring the stock of produced, human, and natural capital in countries across the world is an extremely difficult task. The World Bank undertook this task during 1995 and came up with estimates of total wealth for a group of 108 countries. Figure 2.1 summarizes these results for twelve sub-regions of the world.

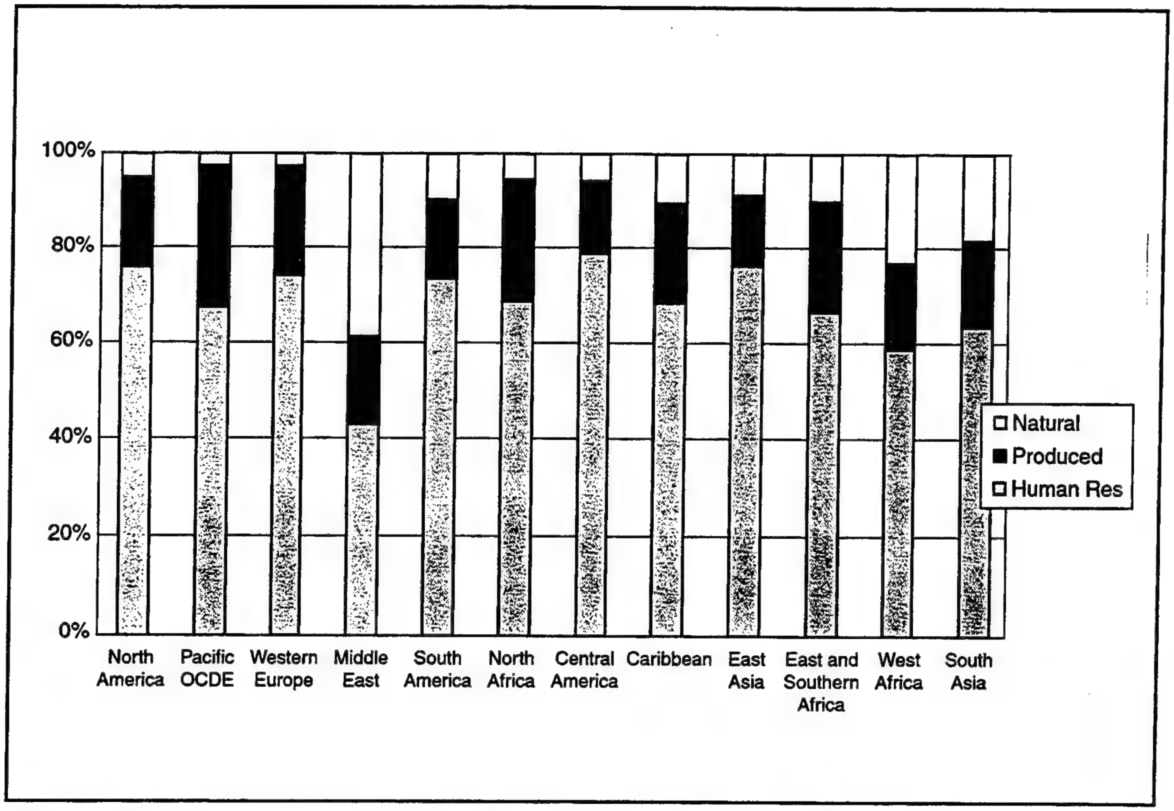

Figure 2.1: Composition of the Wealth of Nations in the World.

Source: Author calculations based on World Bank data (1999).

The figure displays the stock of total wealth per capita and its composition. By and large, the main contributor to the stock of total wealth is human capital, and usually represents between 60% and 80% of total wealth. On the other hand, the relative importance of natural capital with respect to produced capital varies widely across regions. While for OECD countries produced capital represents more than 90% of non-human wealth, in less developed regions, particularly Middle East, Africa and Asia, natural resources represent half of the stock of total non-human capital.

The distribution of wealth in the world is highly skewed. Few countries surpass levels of wealth per capita higher than USD 200,000 and the majority have levels of wealth per capita below USD 50,000 (see Figure 2.2).

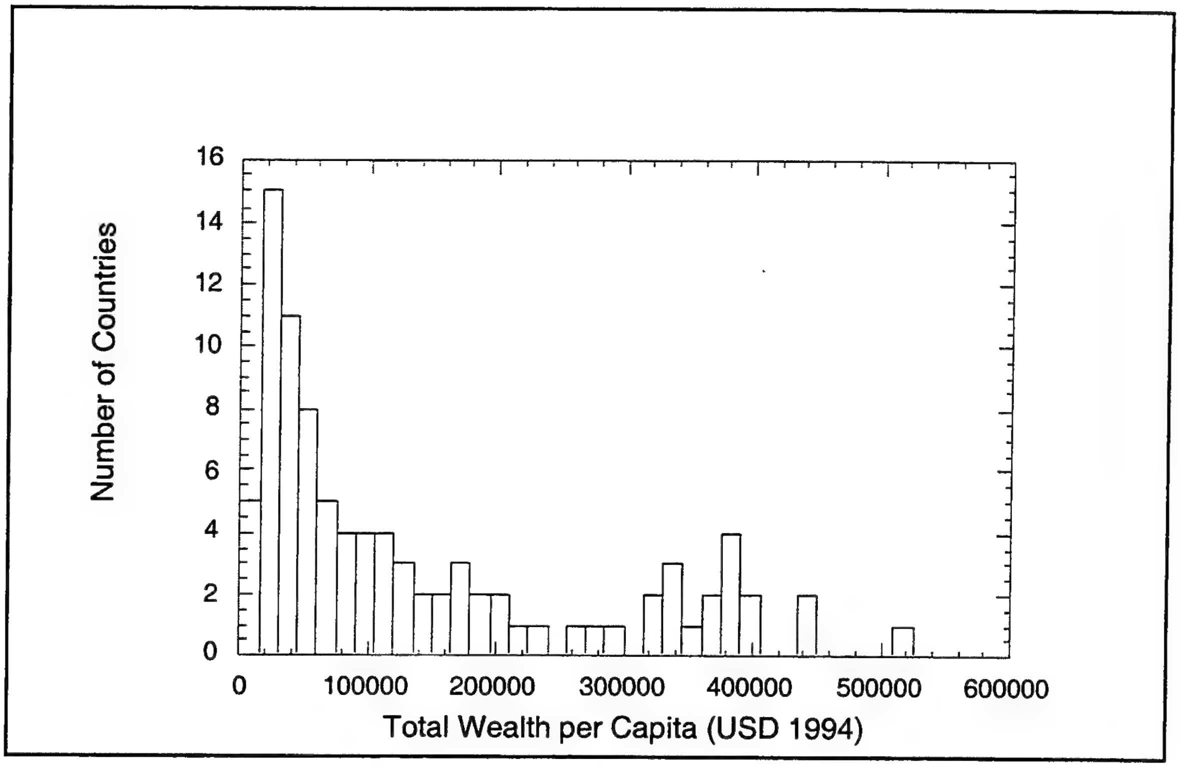

Figure 2.2: The World Distribution of Wealth.

Source: Author calculations based on World Bank data (1999).

This is a source of concern given that available income per capita is tightly related to wealth per capita. To see this, I plot in Figure 2.3 the relationship between the logarithm of the stock of wealth per capita and the logarithm of Gross National Product per capita for countries where the information is available. A simple linear regression suggests that a 1% increase in the total stock of capital per capita is associated with a 1.5% increase in GNP per capita.

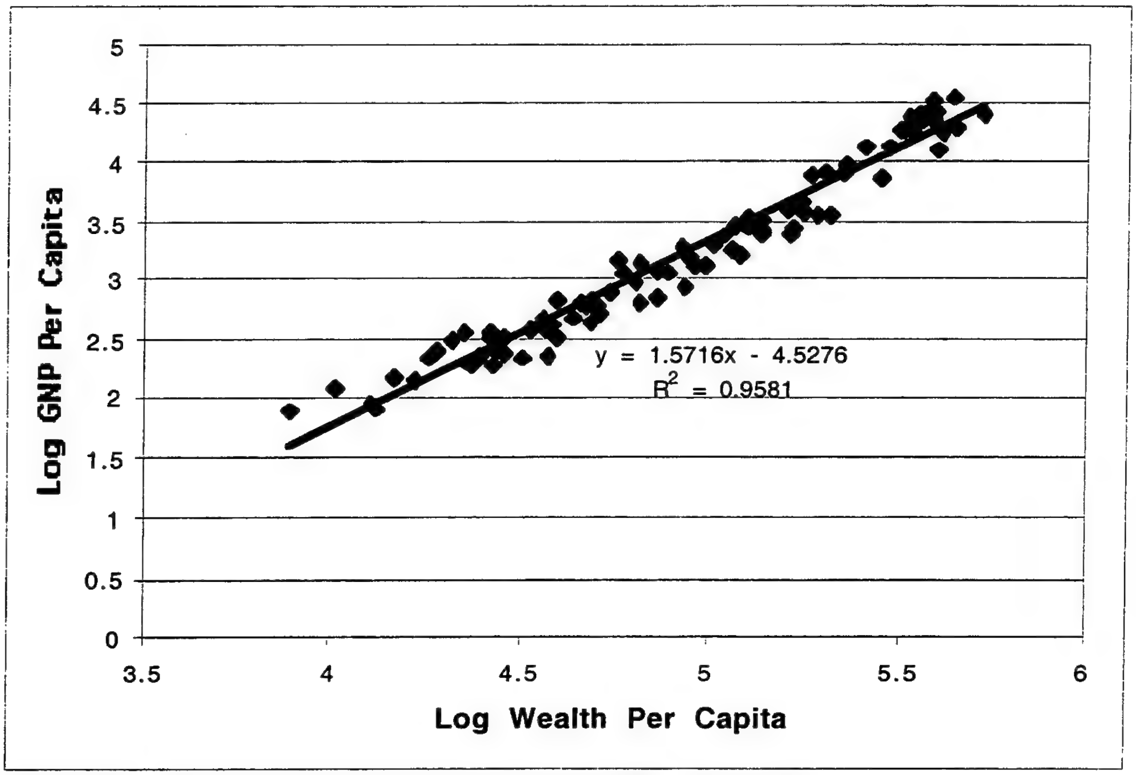

Figure 2.3: Total Wealth per Capita and GNP per Capita.

Source: Author calculations based on World Bank data (1999).

When I break-down the effects of total wealth into the marginal effects of each of its components, human capital per capita appears to be the most important contributor to economic growth. Indeed, using 1994 data, I estimated a "world production function". The results of this simple exercise are presented in Table 2.1. We observe that a 10% increase in the stock of human capital per capita can be associated with an 8% increase in total income per capita. The marginal effect of investments on produced capital is lower but still important. Indeed, a 10% increase in the stock of produced capital per capita, increases income per capita by 6%.

Models	**Coefficient**	**Std. Err**	**Significance**
GNP/Capita			R2=0.95
Human Capital	0.824	0.085	Prob>F=0
Produced Capital	0.604	0.083	
Natural Capital	0.027	0.036	
Constant	-3.268	0.181	

Table 2.1: A World Production Function.

Source: Author calculations.

It is important to notice that once we adjust for differences in the stock of human and produced capital, the stock of natural capital does not have any explanatory power regarding differences in total income per capita. This apparently paradoxical finding is consistent with a well-known result in the literature on development economics, reported for example in Lal and Myint (1996): that countries with a high initial endowment of natural capital have had a tendency to implement policies that infringed on the efficiency of investment, and therefore growth. This was in essence due to inevitable politicization of the rents that natural resources yield. In his 1998 book, Lal refers back to his first study: "In many cases we found that natural resources had proven to be a "precious bone", as they led to policies which tended to kill the goose that laid the golden eggs" (see Lal, 1998). Yet, this is not always true, and this is why the coefficient for natural resources is not negative either. Indeed, a country such as Thailand, also abundant in natural resources, did a good job in transforming rent into long term growth.

3.1 Measuring Produced Capital and Human Capital

Produced capital and human capital have usually been considered as the main factors driving economic development. Produced capital refers to the orthodox concept of capital that includes buildings, machines, roads, bridges, transport equipment, and the like. In the World Bank study, this type of capital was computed on the basis of the perpetual inventory model, with the major inputs being investment data and an assumed life table for assets. On the other hand, human capital refers to human resources and the set of skills and knowledge that they incorporate. In the World Bank study, the value of human resources was obtained as a residual through the following calculation: researchers first multiplied agricultural GDP by 45% to reflect the return of the labor component, and then added all non-agricultural GNP net of rents from sub-soil assets and the depreciation of produced assets. This amount was then discounted over the average number of productive years of the population. The result gives the returns to human capital, produced capital, and urban land. These annual values are converted to a stock using a 4% discount rate. Human

capital is then computed by subtracting from this stock the stock of produced capital and urban land.

Figures 2.4 and 2.5 show the distribution of produced and human capital in the world. Both figures display a very unequal distribution of both types of capital. As shown in Appendix 8.2, in the case of produced capital, while in countries like the United States each member of the population is endowed with roughly USD 76,000 of produced capital, in countries such as Zambia this number is less than USD 3,500. The same is true for human capital, which in essence reflects important differences in labor productivity between the developing and the developed world. Indeed, the majority of countries in the world have levels of human capital per capita below USD (1987) 50,000, while only a minority surpass levels of USD (1987) 200,000 per capita.

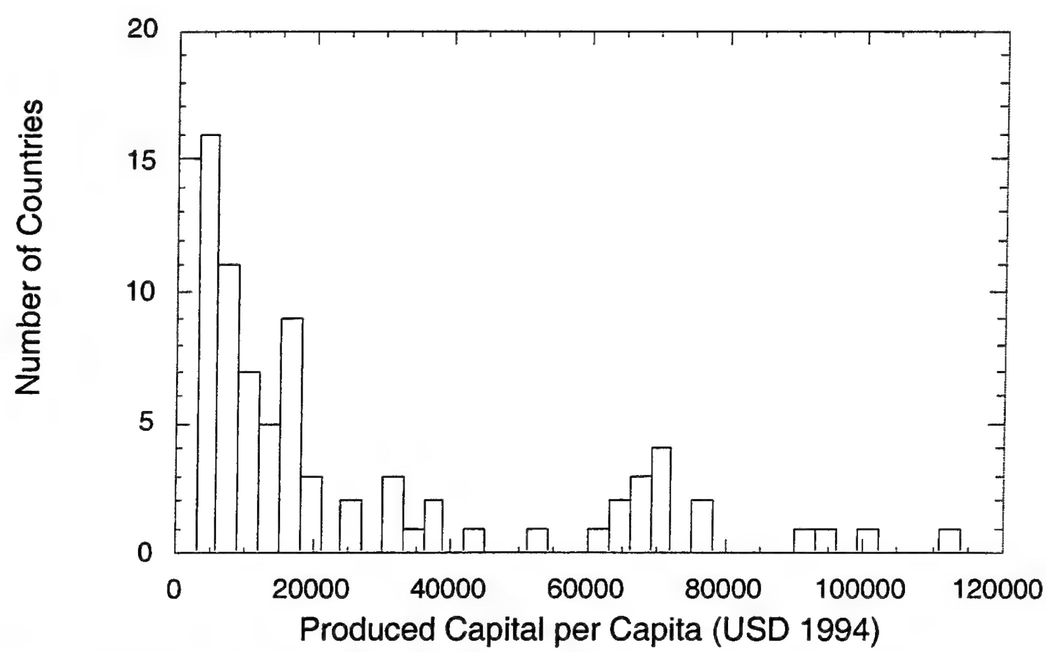

Figure 2.4: Distribution of Produced Capital in the World.

Source: Author calculations.

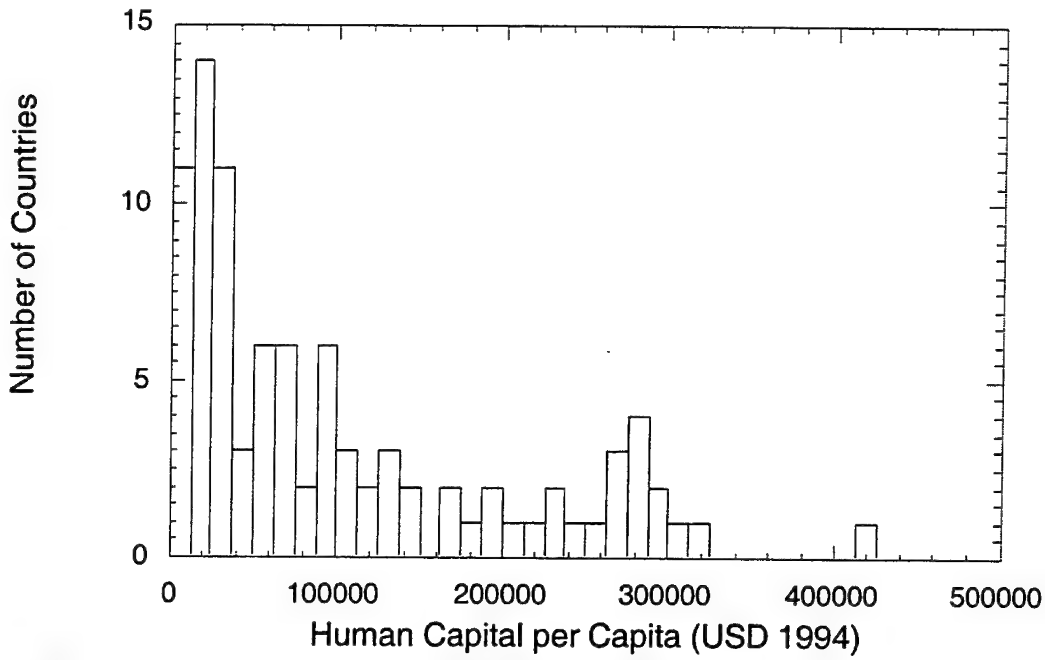

Figure 2.5: Distribution of Human Capital in the World.

Source: Author calculations.

3.2 Measuring Natural Capital

The measurement of the stock of natural capital is probably the main challenge in computing nations' wealth. Natural capital refers to both natural resources and natural services. Natural resources include renewable and non-renewable resources, while natural services refer to those services that are provided "at no cost" by nature. Probably the best example is clean air. In the World Bank study (see Dixon et al., 1998), the stock of natural capital is approximated by a subset of natural resources: agricultural land, pasture lands, forests (timber and non-timber resources), protected areas, metals and minerals, coal, oil, and natural gas.

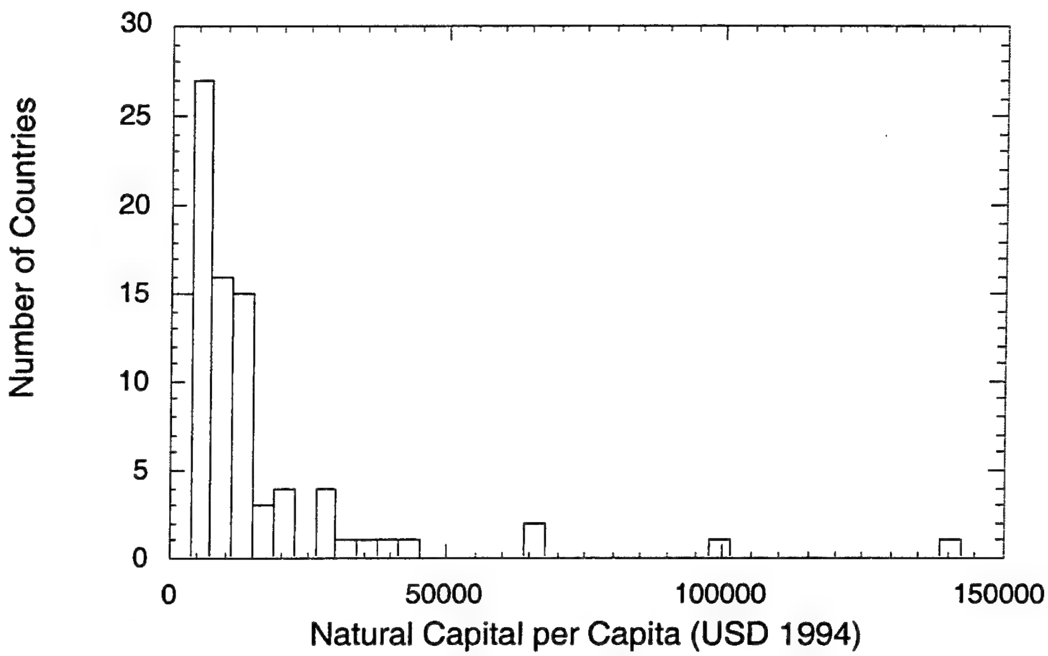

Figure 2.6: Distribution of Natural Capital in the World.

Source: Author calculations.

The availability of natural capital per capita is presented in Figure 2.6. Again, the variance of the indicator is considerable.

In OECD and high income countries, Middle East, and Latin America, the value of natural capital per capita is above USD 6,000. In the last two regions (particularly in the Middle East) this high level of natural capital per capita is mostly explained by availability of oil (copper and zinc are also important in the case of countries such as Chile, Bolivia, and Brazil). In the rest of the world, the value of natural capital per capita is closer to USD 4,000 (see Appendix 8.2).

4. The Dynamics of the Wealth of Nations and Sustainable Growth

4.1 The Need for New National Accounts

From the point of view of sustainable development, the important question is how countries are expanding their wealth to improve the well-being of current and future generations. The dynamics of the wealth of nations depends on investments in the different types of capital and their respective depreciation rates. While standard national accounts take care of the stock of produced capital, no information is provided regarding investments in human capital or desinvestments in natural capital. One of the main methodological contributions of the theory of sustainable development has been to devise methodologies to incorporate these investments to national accounts.

GROSS SAVINGS

=

GROSS DOMESTIC INVESTMENT - CURRENT ACCOUNT AFTER OFFICIAL TRANSFERS

NET SAVINGS = GROSS SAVINGS - DEPRECIATION

GENUINE SAVING I = NET SAVINGS - DEPLETION OF NATURAL RESOURCES

GENUINE SAVINGS II = GENUINE SAVINGS I - COSTS OF CO2 EMISSIONS

EXTENDED SAVINGS III = GENUINE SAVINGS II + INVESTMENTS HUMAN CAPITAL

Box 2.1: Green National Accounts.

Source: World Bank (1998).

Hamilton (1994) develops the concept of genuine savings. Genuine savings are defined as net savings (the standard measure) minus the costs of resource depletion and pollution damages (see genuine savings II in Box 2.1). In an extended version, genuine savings also include investments in human capital (see extended savings III in Box 2.1). Thus, genuine savings address a much broader conception of sustainability than net investment, by valuing changes

in the stock of natural capital and human capital in addition to produced assets (see Pearce and Atkinson, 1993). This new accounting tool allows the introduction of appropriate adjustments to the standard measure of economic performance, the Gross National Product or the Gross Domestic Product. For example, we can define the Green Net Domestic Product (GNDP) as GDP minus the depreciation of produced capital, minus the depletion of natural resources. Notice that as long as depletion rates and depreciation rates are higher than the growth rate of GDP (in real terms), GNDP will be decreasing. We have seen that depletion rates in most countries of the world are above 5% of GDP, while growth rates are below 4% per year. This suggests that the majority of countries are not growing, or even worse are shrinking. In the next two sections, I will review the dynamics of the three components of genuine savings: investments in produced capital, investments in human capital, and desinvestments in natural capital. The purpose is to get a flavor of how countries have been preparing for the future.

4.2 Dynamics of Investments in Human Capital and Produced Capital

The general argument is that in order to increase consumption per capita in the future, investments in produced capital and human capital are needed today. The dynamics of investments in both of these types of capital during the past thirty years is presented in Figures 2.7 and 2.8.

Investment rates in produced capital are highest among East Asian countries, where they average 25-30% of GDP. In other regions of the world, investments rates are closer to 20% of GDP. A general trend for non-Asian countries is a sharp decline in investment rates since the late 1970s. If we consider that capital depreciation rates are usually close to 10%, current investment rates are barely enabling replacement of the stock of produced capital. We may suggest that declining rates in the stock of produced capital are being substituted for investments in human capital.

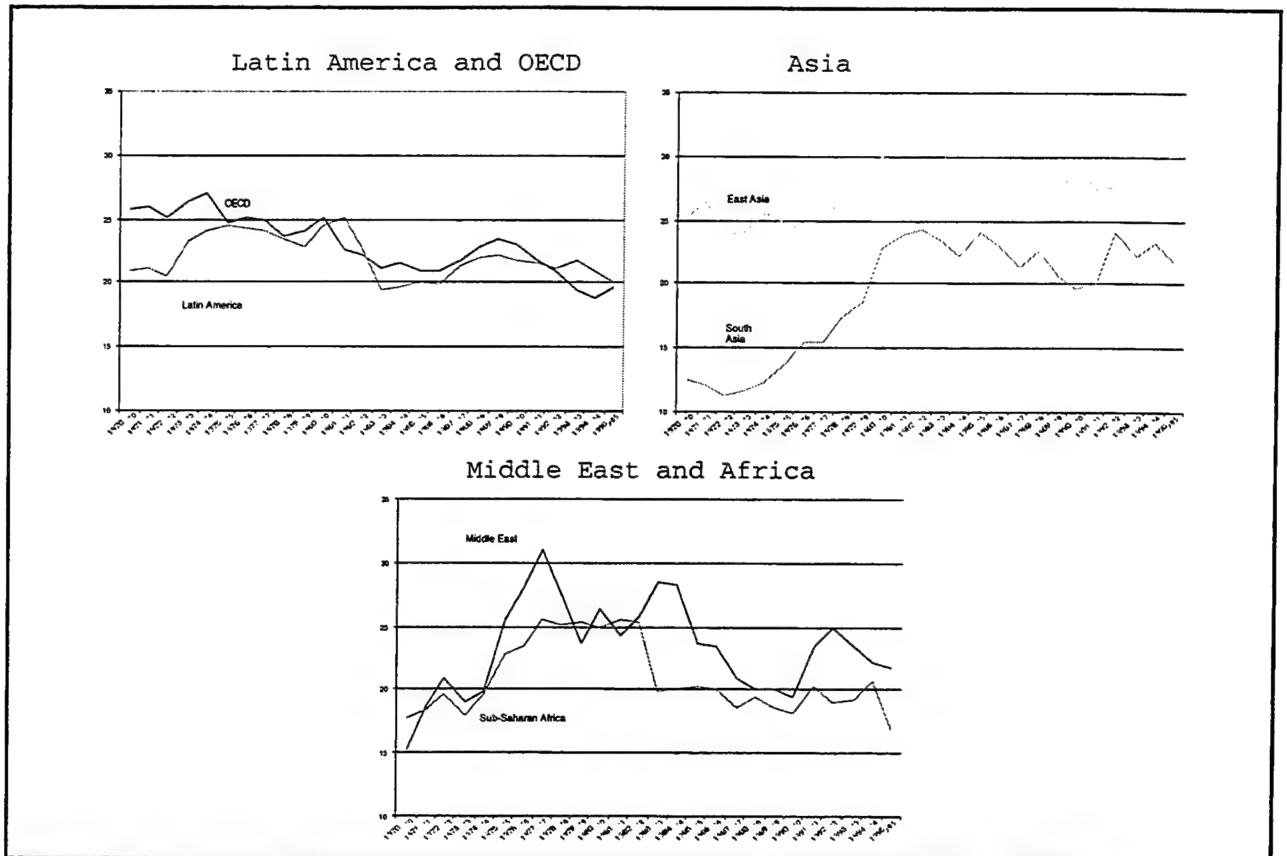

Figure 2.7: Gross Domestic Investment in Produced Capital (% of GDP).

Source: Author calculations based on World Bank data (1997).

However, Figure 2.8 does not support that view. Indeed, investments in human capital have also been falling in most regions of the world (they have remained roughly constant among OECD countries and increased in South Asia). Indeed, during the past ten years, investments in human capital have declined from 4.5% of GDP (the level observed among OECD countries) to less than 2.5% on average.

These reductions in human capital investments can be explained in part by reductions in public expenditures required by the stabilization programs implemented during the '80s (see Krugman, 1999). However, it is unclear whether the economic benefits of higher stability can compensate for the negative impacts on long run economic growth of lower levels of human capital. Meeting the challenge of increasing consumption per capita in the developing world will surely require higher than observed levels of investment in human capital, but also higher rates of return in the marginal dollar invested,

which implies the need for more efficient health and education systems (see Peabody et al., 1999).

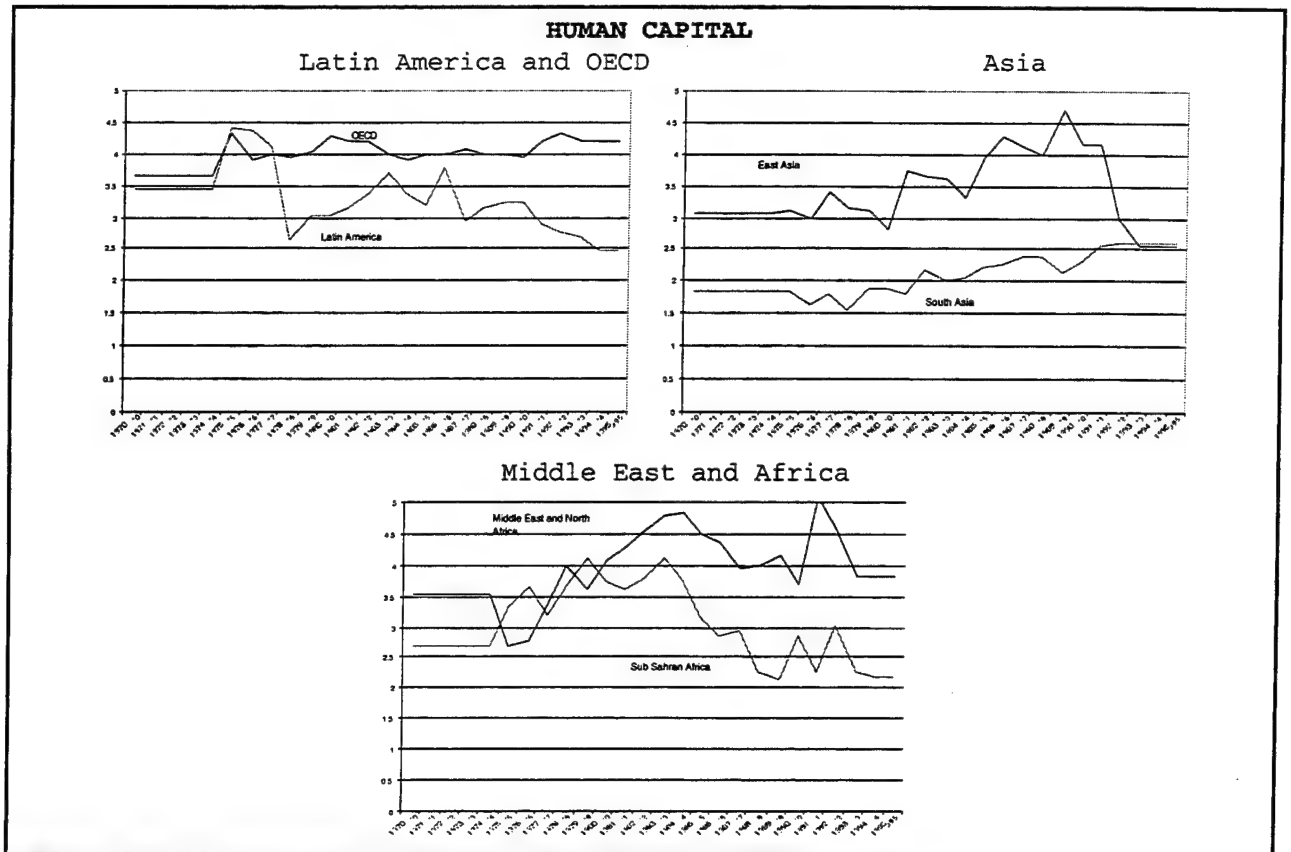

Figure 2.8: Investment in Human Capital (% of GDP).

Source: Author calculations based on World Bank data (1997).

The reader may argue that reductions in investments in human or produced capital are the result of optimal responses to changes in the macroeconomic environment, and that technological progress is compensating for the decline in investments.

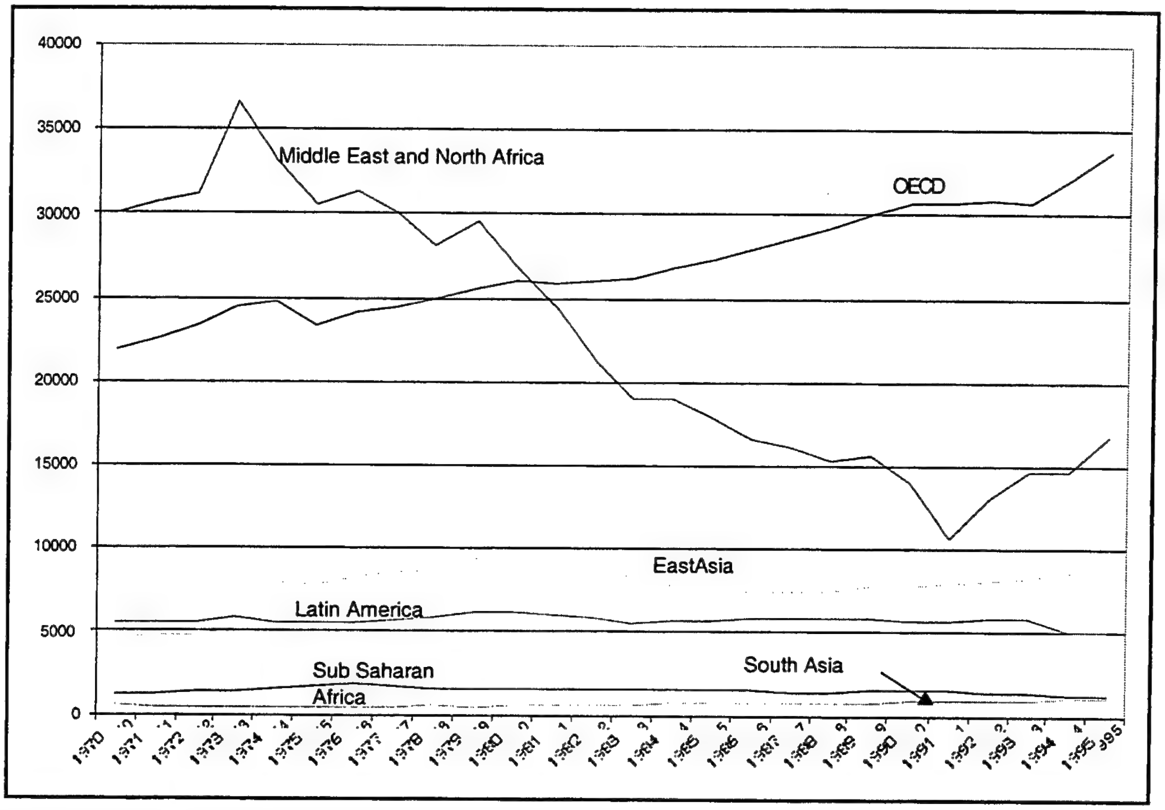

Figure 2.9: Labor Productivity for Different World Regions (USD (1987) per Capita).

Source: Author calculations based on World Bank data (1997).

However, as suggested by Porter and Christensen (1999a), investments in produced and human capital are ultimately the channels through which nations increase their productivity, and in particular labor productivity. Low investment levels imply low productivity growth. This is indeed the picture depicted in Figure 2.9 by the dynamics of the labor/GDP ratio, a proxy for labor productivity, in different regions of the world. The gap between labor productivity in developed countries and labor productivity in the developing world is enormous. While in OECD countries, an average worker produces over USD (1987) 35,000 per year, in Sub-Saharan Africa and South Asia, an average worker produces less than USD (1987) 1,000. During the past two decades, labor productivity has been stagnant in the developing world even in regions that experienced very fast rates of productivity growth in the past, such as Asia that during the '70s. The situation is particularly critical in the Middle East, where high levels of labor productivity during the '70s - resulting from the boom in oil production - have plummeted during the past two

decades. These trends contrast with those of OECD countries, where labor productivity has grown steadily.

4.3 Dynamics of Depletion Rates and Pollution Damages

Resource depletion and pollution reduce the stock of natural resources. Resource depletion is measured as the total rents on resource extraction and harvest. Thirteen types of natural resources were considered in the Dixon et al. (1998) study: bauxite, copper, gold, iron, ore, lead, nickel, silver, tin, coal, crude oil, natural gas, and phosphate rock. For each of these resources, rents were estimated as the difference between the value of production at world prices and the total costs of production, including depreciation of fixed assets and return on capital. Strictly speaking, as explained in Dixon et al. (1998), this calculation measures economic profits on extraction rather than scarcity rents, and for technical reasons gives an upward bias to the value of depletion[2]. Also, non-explicit adjustments are made for resource discoveries, since exploration expenditures are treated as investments in standard national accounting conventions (see Hamilton, 1994). Nonetheless, the bias applies to all countries and therefore the calculations are a reasonable approximation for cross-country comparisons.

Forest resources are taken into account in the depletion calculation as the difference between the rental value of round-wood harvest and the corresponding value of natural growth, both in forests and plantations. Only when harvest exceeds growth is there a depletion charge made for any given country.

In the case of pollution damages, there are several methodological issues to consider. For example, damages to produced capital resulting from acid rain should in principle be included in depreciation figures. However, in practice, most statistical systems are not detailed enough to take this into account. The effects of pollution on output (damage to crops or lost production owing to morbidity) are reflected in the standard national accounting system, although not explicitly. Hence, we do not know how much GDP we are losing as a result of pollution. Rigorously, this value should be

added to current GDP (presumably implying higher gross domestic savings), and then discounted from the new gross domestic savings to compute genuine savings.

The share of pollution costs that is included explicitly in the calculations of genuine savings, is related to its welfare effects. These are given by the willingness to pay to avoid excess mortality and the pain and suffering from pollution-linked morbidity. The marginal social cost of pollution estimated through this willingness to pay for carbon dioxide is close to USD 20 per metric ton. Hence, the part of pollution damages that contributes to the depreciation of natural capital is approximated by Dixon et al. (1998) on the basis of this figure. Therefore, while depletion rates appear to be over-estimated because of the use of economic profits rather than rents, damages due to pollution are under-estimated, but again provide a reasonable benchmark for cross-country comparison.

For my analysis, I have computed what I call pure depletion rates. These rates are computed by subtracting genuine savings II from net savings, and dividing the result by total GDP. Hence, depletion rates represent the amount of natural resources and natural services consumed (including pollution) per unit of GDP produced.

Figures 2.10, 2.11, 2.12, and 2.13 display the dynamics of depletion rates (expressed as a share of Gross National Product) for 11 regions of the world: Middle East (ME), North Africa (NAF), Sub-Saharan Africa (SSA), South Asia (SAS), East Asia and Pacific (EAP), Central America (CAM), South America (SAM), Caribbean (CAR), North America (NAM), High OECD Countries (HOEC), and Western Europe (WE). We observe that in most regions these depletion rates have had a tendency to drop starting in the first half of the '80s, except for North America that experiences a sharp rise at that time. Even in the Middle East, where depletion rates reached levels of 40% of GNP during the '70s, depletion rates dropped to approximately 15% of GNP in 1986. The only regions where depletion rates have remained roughly constant, at relatively low levels, are Sub-Saharan Africa (SSA) and Central America (CAM). Our econometric analysis in Section 5 will address the question of what are the determinants of the dynamics of depletion rates. For now, it is sufficient to

emphasize that while depletion rates have dropped to levels of 1% of GNP in OECD countries, they are still above 5% of GNP in most of the developing world. Furthermore, these estimates should be taken as lower bounds, since as we saw in the previous section, several factors that negatively affect the environment have been excluded from the calculations given data availability.

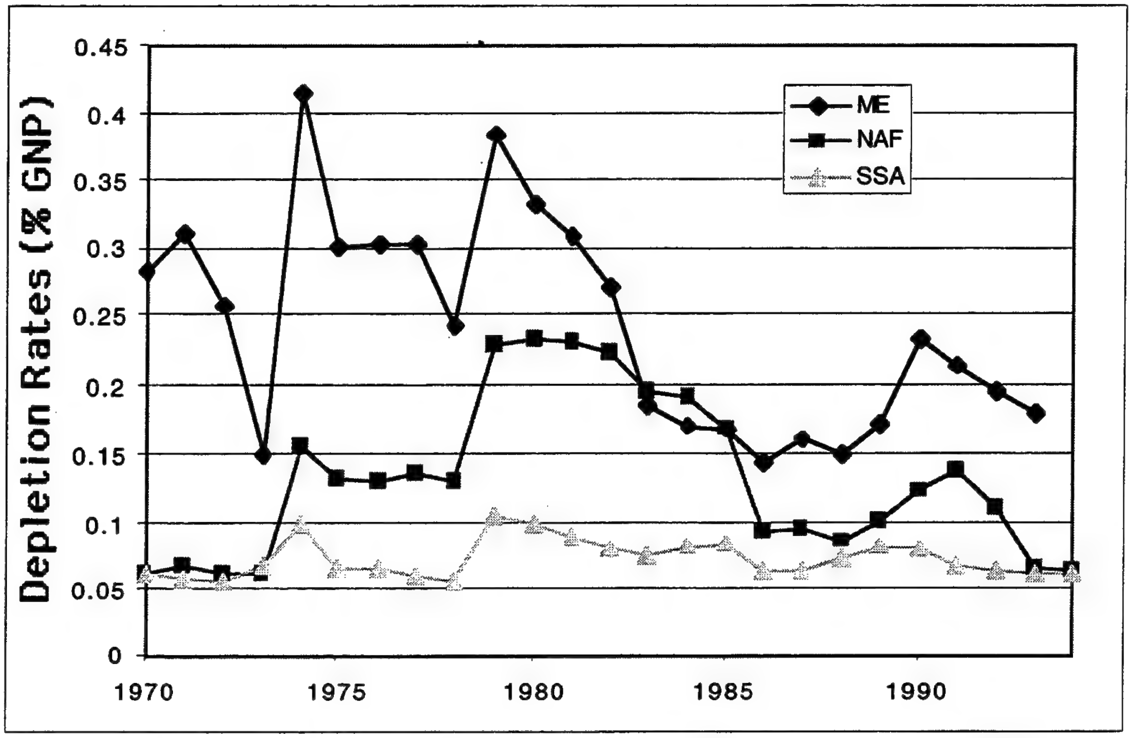

Figure 2.10: Depletion Rates in Africa and the Middle East (% of GNP).

Source: Author calculations.

It is important to notice that for methodological reasons, the depletion rate is not only sensitive to changes in the *quantity* of natural resources consumed and the *quantity* of output produced, but also to changes in prices. More precisely, the depletion rate at a given point in time is computed in real dollars as: $d = \frac{n.p_n}{p} / \frac{No\min alGDP}{p} = \frac{n.p_n}{p} / realGDP$, where p_n is the price of the natural resource, and p is the general price index. Now, assume that the real GDP is constant. Then, the growth rate of the depletion rate is approximately given by: $\dot{n} + \dot{p}_n - \dot{p}$ (where the dot over the variable means "growth rate"). If the growth rate of the price of output is not equal to the growth rate of the price of the natural resource, the growth rate of the depletion rate will be distorted. For example, countries that preserve a fixed n/GDP ratio may seem

to be reducing their consumption of natural resources per unit of GDP if the price of natural resources p_n is dropping faster than the general price index p. This is a problem that affects our measurement of real GDP as well. Unfortunately, there is little that we can do to avoid this bias, and hope that divergences between p and p_n are not very important.

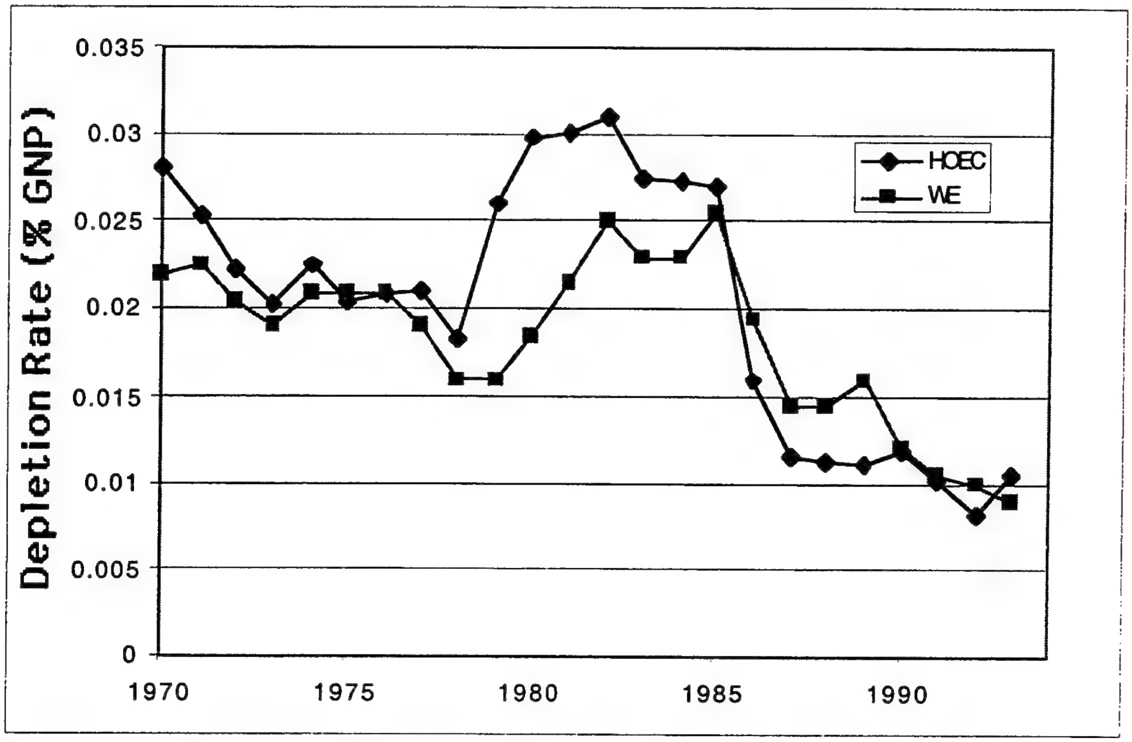

Figure 2.11: Depletion Rates in OECD and Western Europe (% of GNP).

Source: Author calculations.

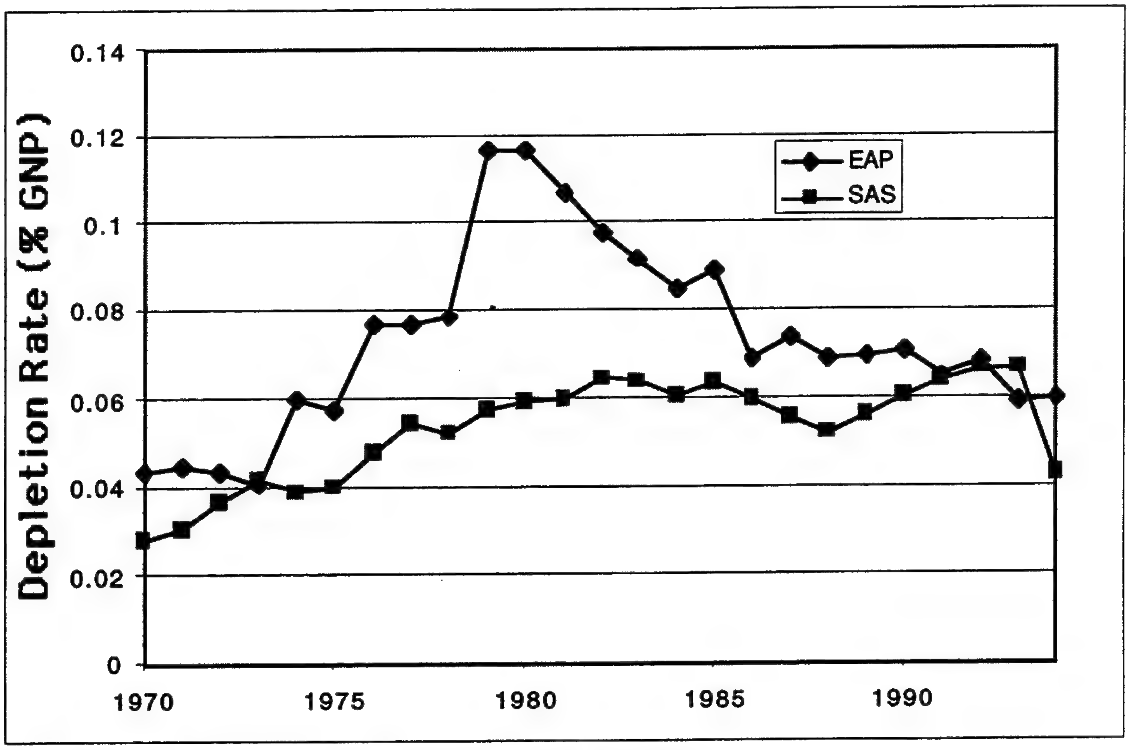

Figure 2.12: Depletion Rates in Asia (% of GNP).

Source: Author calculations.

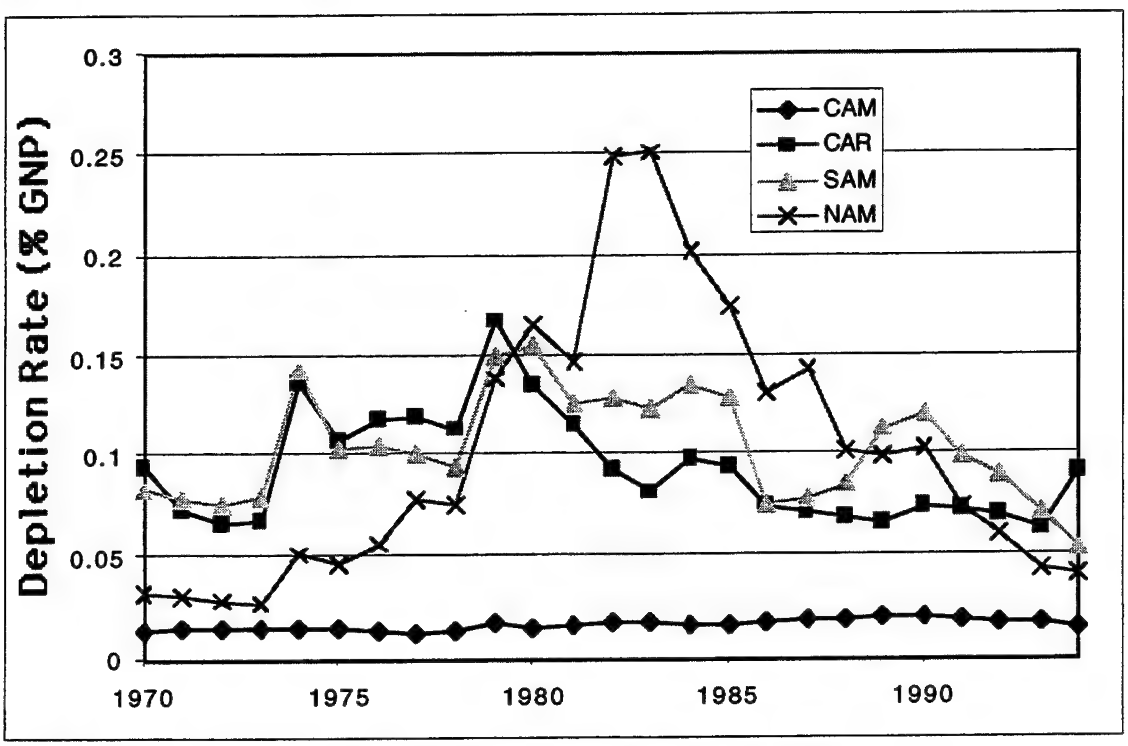

Figure 2.13: Depletion Rates in the Americas (% of GNP).

Source: Author calculations.

The effects of poor environmental management are felt dramatically in many developing countries. The amount of agricultural land now being lost outright through soil erosion is estimated at a minimum of 20 million hectares per year (see Myers, 1994). This phenomenon is disastrous, since hundreds of years are required to renew a mere 25 millimeters of soil, or the equivalent of 400 tons of soil per hectare (see Hudson, 1981). It has been estimated that from 1985 to 2000, losses may reach a cumulative total of 540 million hectares (see Sfeir-Younis, 1986). The critical regions are the Andes Mountains, the Yellow River basin in China, and the Indian Deccan.

Another serious problem is deforestation. During the twentieth century, forest surface has been cut in half in developing countries, aggravating problems such as soil depletion, flooding, sedimentation, and threatening the life of countless species of plants and animals (see Pearce and Markandya, 1994). It has been estimated that most of the forested areas of Bangladesh, India, the Philippines, Sri Lanka, and parts of Brazil could be gone by the middle of the next century (see Mahar, 1994). Water is also a source of concern, particularly in cities such as Bombay, Cairo, Lagos, Sao Paulo, and those at the frontier of Mexico and the United States. In the latter, intense economic activity resulting from the "maquiladora" industry and an unprecedented growth of the population have brought several environmental problems (see United States - Mexico Chamber of Commerce, 1996). Emissions of greenhouse gases are also a critical problem in the developing world. Different studies suggest that in 2050, close to 70% of human greenhouse gas emissions will be generated in the developing world, especially in China, India, and Brazil (see Manne and Ritchels, 1998).

The poorest countries, which tend to be heavily dependent on their natural resource base and have relatively high rates of population growth, are the most vulnerable to the effects of environmental degradation. This is due in part to the fact that shortages of capital and trained manpower (resulting in part from low risk adjusted rates of returns to investments) severely limit their ability to switch to other economic activities when their natural resources can no longer sustain them (see Wadford, 1994).

5. Econometric Analysis of Determinants of Depletion Rates

While investments in human and produced capital will be crucial for sustainability, a more detailed empirical analysis of the determinants of their dynamics lies outside the scope of this research. The reader is referred to Little et al. (1993), Bosworth (1993), and Fedderke and Luiz (1999). My focus in the remainder of this chapter will be on the less studied phenomena of the dynamics of depletion rates.

What are the determinants of depletion rates? A first simple story that one could tell is that in a competitive economy, the quantity of natural resources consumed depends on their marginal cost relative to the marginal cost of other inputs. Because marginal costs reflect scarcity, it follows that countries with higher initial endowments of natural resources will tend to have higher depletion rates (i.e., higher consumption of natural resources per unit of output). If we take the case of a fixed stock of natural resources, as this stock is depleted and presumably invested in other forms of capital, the cost of natural resources should increase, and their demand should decrease relative to the demand of other inputs. Hence, over time, we should observe falling depletion rates. If the stock of natural resources is not fixed, due for example to new discoveries, depletion rates may be growing for a while but after some period of time one should expect that the stock of natural capital will stabilize, and that depletion rates will start to fall.

The truth of the matter, however, is that developing economies have not been competitive, at least in early stages of development, and that governments have actively been involved in regulating the economy. Hence, a more realistic story, more in line with the theories of structural change (see Lewis, 1954; Kuznets, 1965; and Chenery and Taylor, 1968) is as follows: given low levels of human and produced capital, countries at low levels of development tend to be intensive in their natural resource base. Domestic output and exports are highly dependent on resources such as land, fisheries, forests, metals, and minerals. During the '70s, developing countries had a tendency to reinforce this model of growth, in hopes of stimulating the development of the industrial sector. Very often, governments provided

generous subsidies for natural inputs that accelerated the rise in depletion rates. Also, it was common for governments to be involved in the extraction of these natural resources, using the rent to finance infrastructure projects. For example, during the '70s, in countries such as Mexico, Venezuela and Ecuador, up to 50% of GDP was linked to the oil industry, owned and managed by the public sector. Unfortunately, in many cases, rents from the extraction of natural resources were not invested in projects with the appropriate rate of return. Governments expanded unproductive bureaucracy, or constructed hospitals for electoral purposes without assessing the proper level of future investments required to keep the facilities running.

In a second phase starting roughly after the 1982 Mexico financial crisis, the international community started to embrace market driven reforms. This process has gained momentum particularly during the last decade. Hence, some developing countries have started to eliminate market distortions such as subsidies for natural resources (see Chapter 4). At the same time, for some countries, growth has brought a change in the sectorial composition of the economy, where the share of agriculture and natural resource intensive industries has fallen to give rise to the services and the manufacture sectors that are intensive in knowledge and technology.

This suggests that for the past two decades, changes in depletion rates in the world should reflect changes in the sectorial composition of the economy, but also changes in the legal and institutional framework that regulates the exploitation of natural resources. I will argue that the effectiveness of policies such as those attempting to "get the prices right" will be in part related to countries' capacity to absorb new production technologies. Factors that influence this absorption capacity include the strength of the financial sector and countries' stock of social capital (see Chapter 3 for a discussion of this topic). I will test these ideas in the next section.

5.1 Economic Development and Depletion Rates

I have argued that in the early stages of development countries tend to intensify the use of natural resources, but that after some level of economic development, two phenomena take place: a) the sectorial composition of the economy changes, increasing the shares of modern manufacture and services

sectors; and b) institutions and policies change in order to rationalize the use of natural resources. These two phenomena suggest that depletion rates should follow an inverted U-shaped dynamics over a country's development toward a modern economy (Kuznets hypothesis). This is similar to the inverted U-shaped dynamics that one observes in the case of pollution (see John and Peccheniono, 1992; and Seldon and Song, 1995).

In this section, I test this idea empirically. The model that I develop closely follows the model developed by Hettige, Huq, Pargal, and Wheeler (1997). The idea is that the sum of the natural resources and natural services consumed by country i at time t, can be represented by a function of the form:

$$D_{it} = \sum_j s_j(Y)Q\lambda_j(Y)\eta(Y), \tag{2.3}$$

where s_j is the share of an economic sector j (i.e., agriculture, industry, manufacture, and services) in total value added Q, λ_j is the depletion intensity of the sector (the quantity of natural resources required to produce one unit of output in the absence of regulations), and η is the abatement intensity of the economy (the share of the quantity of natural resources per unit of output that the private sector can effectively extract). All are assumed to be functions of the level of economic development that is itself approximated by GDP per capita (Y).

As countries develop and Y increases, we observe a shift in the share of the different sectors within the economy. Usual patterns are that the share of the agricultural sector and the intensive extractive industry diminishes while the shares of the manufacture and services sectors rise (see Gillis et al., 1992). Given that depletion intensities for the services and manufacture sectors are lower than for agriculture and extractive industry, this pattern of growth is accompanied by a reduction in depletion rates. At the same time, the abatement intensity of the economy increases as institutions grow stronger and social organizations interested in preserving the environment develop (see Cameron and Carson, 1999).

To have an empirically estimable relationship, I divide equation (2.3) by Q and thus get an expression for the depletion rate: $d_{it} = \frac{D_{it}}{Q_{it}}$. Given that d_{it} is a share that has to be constrained to lie between 0 and 1[3], for estimation purposes, I use the transformation:

$$\log\frac{d_{it}}{1-d_{it}} = \log\left(\frac{f(Y)}{1-f(Y)}\right) = g(\log Y). \tag{2.4}$$

As in Hettige et al. (1997) I approximate (2.4) by:

$$\log\left(\frac{d_{it}}{1-d_{it}}\right) = \alpha_0 + \alpha_1 \log Y_{it} + \alpha_2 \left(\log Y_{it}\right)^2 + v_i + u_t, \tag{2.5}$$

which can be interpreted as a second order expansion of g(.). We verify that $\frac{\partial[d/(1-d)]}{\partial d} = \frac{1}{1-d} - \frac{d}{(1-d)^2} \geq 0$ since d<1. Therefore, when d increases (decreases), 1/(1-d) increases (decreases). The Kuznets hypothesis implies $\alpha_1 > 0 \wedge \alpha_2 < 0$.

I estimate model (2.6) on the basis of a panel data for 104 countries in the world. For each of these countries I observe several economic, social, and environmental indicators, during the period 1970-1994. Table 2.2 summarizes the mean of a selected set of variables. For this part of the analysis, I work exclusively with depletion rates and GDP per capita.

Because model (2.5) is a panel model, it is well known that the Ordinary Least Square method will produce bias estimates, as long as the error terms are correlated. Very often, this is the case with panel models, where for each country, the error terms tend to be correlated over time. At the same time, the variance of the random shocks tends to differ across countries. Two of the most popular alternatives for estimating (2.5) are fixed effects models and random effects models. The choice between the two is given by the variance of v_i. If the variance is zero, one should prefer fixed effects models, but if the variance is different than zero, the random effects model

is the preferred choice. It turns out that in the case of our data set, the variance of v_i is significantly different from zero. Hence, there are systematic non-random shocks that affect the intercepts of the equations. Therefore, I have estimated a random effects model by Generalized Least Square methods.

1970												
Var	Central America	Caribe	East Asia Pacific	High Income OCDE	Middle East	North Africa	North America	South America	South Asia	Sub-Saharan Africa	Western Europe	World
depleGDP	.0143333	.0936	.0431111	.0280952	.2833333	.0625	.033	.0822727	.0284	.0616923	.022	.0590778
GDP_Cap	-	-	-	-	-	-	-	-	-	-	-	-
highX	7.611825	42.26666	10.85663	18.45546	6.249722	4.982099	31.35709	24.0306	2.811683	8.840547	13.76599	14.23566
agr_GDP	31.48018	11.50902	29.54434	5.802078	12.13279	19.27868	11.64927	16.35246	46.43003	34.75465	39.53905	26.94659
ind_GDP	24.23433	33.10857	25.99567	42.84767	37.75382	29.31006	29.43633	34.4494	17.65767	22.43799	20.12959	26.86499
ser_GDP	44.28549	55.38241	44.45999	51.19771	50.11339	51.41125	58.91441	49.19814	35.9123	42.80736	40.33135	45.57111
man_GDP	20.18854	16.9466	16.59309	29.13087	9.926659	13.26349	22.04593	21.10364	11.44181	10.8963	12.45293	15.2538
m3_GDP	19.54733	28.41413	30.99462	58.01651	38.90797	37.84535	15.03131	20.42839	25.03365	18.45353	29.21329	30.82221
acc_GDP	-	-14.9452	-	.0290264	-10.79747	-5.883508	-	-2.694249	-2.356637	.0862131	-	-3.188113
debtX	-	8.291956	17.56966	-	-	27.27548	-	14.10428	20.0127	3.363973	-	14.209
urbPop	41.4	38.98333	37.53	70.4	57.88333	40.175	59	58.27273	15.62	18.75333	45.45	41.928
popKm	65.02763	241.6721	767.8388	107.8438	86.62994	26.56937	26.36782	11.4751	209.6001	41.07873	57.05457	149.0886
x_GDP	23.87539	33.30474	33.25578	28.1723	36.25558	18.95196	6.409186	18.96066	10.03312	26.75977	6.025508	25.46306
c_GDP	75.9474	72.07592	67.70211	58.04176	53.43263	64.92327	74.78079	69.89485	76.86081	71.30086	76.69368	68.34762
g_GDP	10.41312	11.80868	12.28651	14.50019	23.00861	17.13248	6.534447	11.27462	11.07208	13.79531	9.52013	13.44492
fI_GDP	1.135314	6.397242	.5551989	1.161758	.1308843	.6450139	.8429019	-.3517303	.0740427	.1866476	.3694463	.7356513
m_GDP	25.77232	39.99923	39.4743	28.30319	29.58909	23.53204	8.977036	18.5391	13.69475	29.56262	10.86575	27.69729
Dcpi	3.271495	5.94426	5.988231	5.398737	3.35464	3.880718	5.211781	8.175584	6.909867	3.361851	4.923772	5.144348
taxGDP	9.331638	-	13.75706	24.11334	-	15.94326	-	11.91722	18.34748	17.2189	9.972418	19.48824
soe_GDP	-	-	-	-	-	-	-	-	-	-	-	9.36655

Table 2.2: Means by Decade and Region.

Source: Author calculations.

depleGDP = Depletion rate
GDP_Cap = GDP per capita (USD (1987))
highX = Share of High tech exports in total exports
agr_GDP = Share of agriculture in GDP
ind_GDP = Share of industry in GDP
ser_GDP = Share of services in GDP
man_GDP = Share of manufacture in GDP
m3_GDP = Extended money supply(M3)/GDP ratio
acc_GDP = Current account balance as a percent of GDP
debtX = External debt payments as a share of exports

urbPop = Urban population
popKm = Population per Km
x_GDP = Exports as a share of GDP
c_GDP = Consumption as a share of GDP
g_GDP = Government expenditures as a share of GDP
fI_GDP = Investments as a share of GDP
m_GDP = Imports as a share of GDP
Dcpi = Inflation as a share of GDP
taxGDP = Tax revenues
soe_GDP = Value-added of State-owned enterprises in GDP

1980												
Var	Central America	Caribe	East Asia Pacific	High Income OCDE	Middle East	North Africa	North America	South America	South Asia	Sub-Saharan Africa	Western Europe	World
depleGDP	.0163433	.0974571	.077773	13055.02	.2383	.1441316	.1155789	.1088086	.0522737	.0753752	.0198421	.0758728
GDP_Cap	2862.773	3753.013	4484.304	21.71669	7022.746	2807.314	5983.793	4291.811	852.2281	1603.722	5781.891	5200.157
highX	11.99212	32.0369	21.38122	4.648171	12.02953	14.37581	33.24248	15.49342	2.2696	9.946551	9.143168	16.13829
agr_GDP	25.86937	10.79158	23.85983	34.37008	11.08347	16.92315	9.199292	14.88063	41.06439	33.58267	27.04226	23.22082
ind_GDP	25.26834	32.07969	32.33224	60.78123	39.39201	34.48655	31.15928	36.32426	20.44791	23.8195	24.51353	29.2521
ser_GDP	48.86229	57.12874	43.80794	22.81547	49.52451	48.5903	59.64143	48.79511	38.4877	42.59782	48.44421	46.91925
man_GDP	19.0735	13.30447	20.604	62.70392	9.818759	14.19952	22.27157	21.84038	12.8841	11.31175	16.05357	16.0582
m3_GDP	31.33079	36.40754	38.57805	-1.474901	54.27276	53.82762	22.58302	27.52486	30.32501	23.01051	35.95599	37.61425
acc_GDP	-3.581813	-5.090728	-3.545765	-	.8099487	-6.481571	-1.291856	-2.930776	-3.56822	-6.880749	-2.994964	-3.85863
debtX	19.44643	13.39192	23.6221	73.31754	10.8107	25.73847	44.36989	33.85977	16.29821	18.4123	28.30498	21.1932
urbPop	42.81184	43.09825	42.55263	113.7112	65.14825	45.12895	66.13158	63.7823	18.08211	24.03947	51.79737	46.49363
popKm	82.48693	261.8875	955.4622	32.67582	131.0657	33.72106	34.97672	14.35851	268.4661	52.14528	66.23345	181.3241
x_GDP	30.35291	37.7117	47.63113	58.89373	41.00919	25.42299	12.13959	20.72507	12.36023	27.9877	11.89479	30.13039
c_GDP	72.77703	69.41155	59.64402	17.09703	54.53556	61.3407	68.77735	66.58852	79.87265	72.37776	75.88377	66.75531
g_GDP	13.10006	14.39561	12.47991	.8941052	24.78455	16.73422	8.668796	11.9573	9.309295	15.30925	10.89421	15.0272
fI_GDP	1.142298	1.89086	2.025499	33.01184	.2121173	1.032549	.8885797	.3526503	.1529952	.7747348	.5529677	.8766113
m_GDP	35.70243	44.44082	48.93097	8.423531	45.58088	32.46068	11.32361	21.08239	19.4645	35.48209	17.99453	34.23442
Dcpi	13.42601	12.30752	9.495933	28.14739	23.50742	9.705055	43.79636	171.5604	10.67961	16.42806	27.738	32.30065
taxGDP	13.63809	20.25536	14.62501	6.739024	17.66714	22.47711	12.5743	15.10861	10.90857	15.24095	18.45426	18.89842
soe_GDP	4.016465	9.566667	9.368046	-	-	24.58	6.700043	9.634425	7.776729	10.90105	7.099975	9.602372

Table 2.2: Means by Decade and Region.

Source: Author calculations.

1990												
Var	Central America	Caribe	East Asia Pacific	High Income OCDE	Middle East	North Africa	North America	South America	South Asia	Sub-Saharan Africa	Western Europe	World
depleGDP	.0177778	.0735	.0648696	.0102143	.1926957	.10125	.0646	.0877593	.0607917	.0678169	.0104444	.0638455
GDP_Cap	3202.34	3770.666	6903.709	15366.06	6728.906	2956.078	6071.585	4813.98	1062.682	1542.012	6643.528	6028.848
highX	14.89918	34.13533	36.176	27.6995	24.87483	14.34838	32.91305	15.62286	3.220862	12.98632	9.63376	22.1908
agr_GDP	19.11975	13.81513	18.56905	2.881679	11.31828	15.50479	5.944369	11.80107	31.61164	31.59047	16.44355	20.41521
ind_GDP	24.56893	29.13567	34.70153	30.23087	33.80712	34.8663	25.50377	33.58305	23.37138	24.79115	30.33183	28.56649
ser_GDP	56.31132	57.0492	46.72942	66.54488	54.62371	49.62891	68.55186	54.61588	45.01698	43.61838	53.22462	50.03196
man_GDP	19.0195	12.39168	22.24459	19.72345	14.83107	17.46084	18.55017	21.00384	13.78844	12.54961	19.68986	16.33243
m3_GDP	36.08584	46.23607	72.73254	72.95894	69.20162	59.29867	27.27379	34.58739	38.57414	23.43823	38.22058	45.97966
acc_GDP	-3.858115	-2.56674	.0309521	.2313765	-4.373978	-1.490436	-4.038618	-1.54460	-4.602852	-5.56666	-1.521961	-2.68078
debtX	13.5907	14.66789	18.07157	-	12.53344	30.80901	29.35585	27.02612	18.34096	22.18832	28.988	21.38287
urbPop	44.62286	49.33571	49.91057	75.56531	73.35476	52.26786	73.04286	70.85662	21.69029	31.07224	62.5	52.27767
popKm	106.3815	294.074	1187.75	120.0989	200.04	45.10919	46.29924	18.47568	353.7163	69.65635	78.78698	224.4429
x_GDP	32.79629	37.68639	59.60122	35.31201	48.6974	29.6206	19.33896	19.75638	17.80542	28.4271	16.69675	32.99422
c_GDP	74.47928	70.54143	54.74153	59.62152	55.18317	64.69198	74.39067	70.53189	74.59415	76.06843	73.08039	68.38073
g_GDP	11.67564	12.33594	11.30787	18.34061	23.07539	14.96605	4.758887	10.14153	11.33994	14.20681	12.96118	14.34156
fI_GDP	1.897618	3.358471	3.764922	1.497761	.2995172	1.154868	1.860615	.7514475	.4596842	.6987771	.7592496	1.343065
m_GDP	40.28088	42.84583	58.84719	33.10279	53.42022	33.67512	21.11549	19.73384	24.61471	36.18488	23.43773	36.49638
Dcpi	13.56126	15.48461	8.92402	3.277935	10.11016	12.50802	21.55956	277.9429	9.718115	17.99075	45.38483	42.86034
taxGDP	14.94051	18.99224	14.56085	31.38419	17.0138	22.90612	13.38157	15.40457	12.24104	16.10065	16.59297	20.17415
soe_GDP	6.1719	17.06667	3.300331	6.166667	-	25.86667	4.880857	8.060964	7.068017	12.26945	5.052845	8.531067

Table 2.2: Means by Decade and Region.

Source: Author calculations.

Description	Coef.	Std. Err.	P>|z|	Number of obs	R-sq within
Simple version (no time effects) χ = 0.0000				1397	0.1313
log(Y)	4.16736	0.7481575	0.000		
log(Y)^2	-0.3149549	0.0459373	0.000		
_cons	-16.26304	3.031062	0.000		
Extended version (time effects) χ = 0.0000				1397	0.3747
log(Y)	2.924027	1.117548	0.009		
log(Y)^2	-0.163493	0.0704243	0.020		
log(Y)*t	-0.2093404	0.0426656	0.000		
log(Y)^2 * t	0.0105802	0.0026572	0.000		
t	0.9370649	0.1691579	0.000		
_cons	-15.36133	4.396594	0.000		

Table 2.3: Regression of Kuznets Hypothesis.

Source: Author calculations.

The results of the estimation are presented in the first panel of Table 2.3. We observe that the parameters for $\log(Y)$ and $(\log Y)^2$ are not only individually highly significant, but jointly significant as well (the χ statistic is zero). Hence, the data seems to support the idea that, at low levels of economic development, depletion rates increase, and that they diminish as further economic growth takes place. To better illustrate this idea, I graph the depletion rate as a function of GDP per capita in Figure 2.14. The adequate transformation of (2.5) is:

$$d_{it} = \frac{e^{\alpha_0 + \alpha_i \log Y_{it} + \alpha_2 (\log Y_{it})^2}}{1 - e^{\alpha_0 + \alpha_i \log Y_{it} + \alpha_2 (\log Y_{it})^2}} \tag{2.6}$$

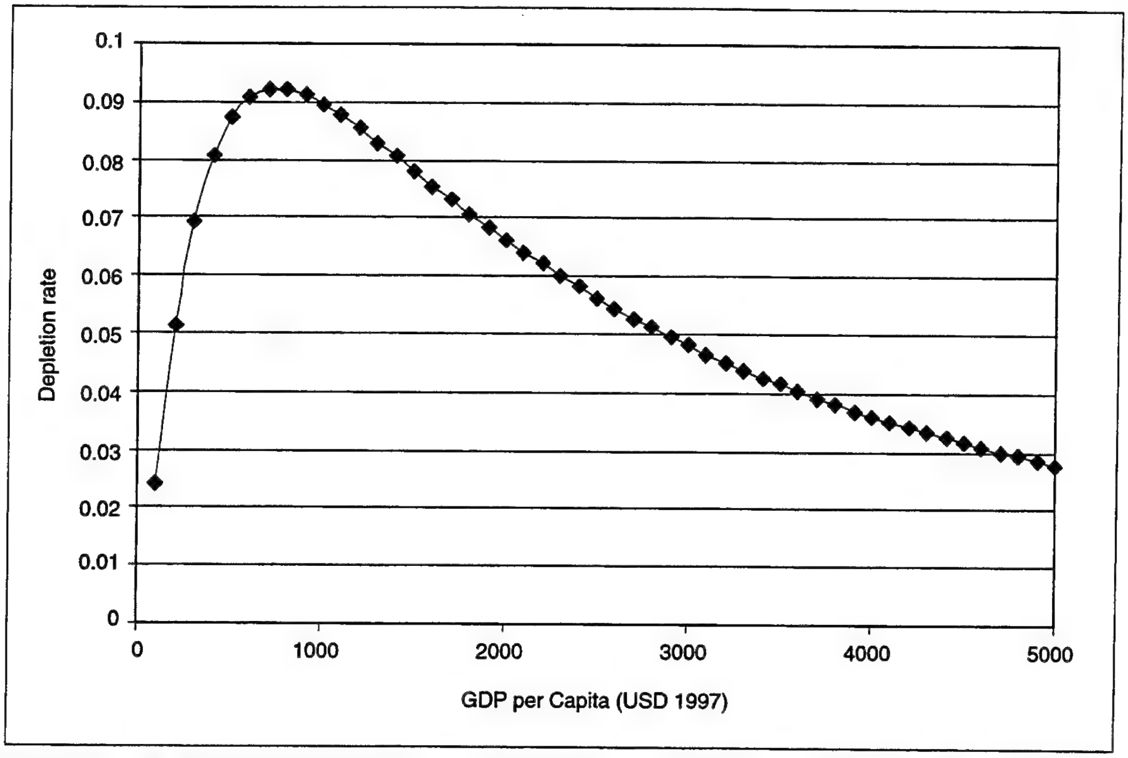

Figure 2.14: Depletion Rates as a Function of GDP per Capita (% of GDP).

Source: Author calculations.

The figure suggests that depletion rates tend to rise for levels of income below USD (1987) 1,000 per capita, and tend to decrease for higher levels of income per capita.

This simple model can be modified slightly to allow for the possibility of technological progress, or "accumulation of knowledge". The idea is that independently of the level of income, time should bring lower depletion rates that result, presumably, from the adoption of more environmentally friendly technologies, or simply better policies to manage the stock of natural resources. To model this phenomena it is enough to add an additional variable, a normalized time index (starting at 1 and increasing by one each year), to model (2.5). However, it is also reasonable to expect that technological progress will have different effects depending on the level of income. In other words, if less developed countries use different technologies, then the effect of technological progress on the depletion rate should be different for lower levels of Y. This suggests that one should also

include interactions between time and the level of GDP per capital. Therefore, we rewrite (2.5) as:

$$\log\left(\frac{d_{it}}{1-d_{it}}\right) = \alpha_0 + \alpha_1 Y_{it} + \alpha_2 Y_{it}^2 + \alpha_3 Y_{it} t + \alpha_4 Y_{it}^2 t + \alpha_5 t + v_i + u_{it}\,, \tag{2.7}$$

where t is the normalized time index[4].

The results of the estimates of model (2.7) are presented in the second panel of Table 2.3. Statistically, this model appears to be more robust (the R^2 is three times higher). Again, we verify that $\alpha_1 > 2$ and $\alpha_2 < 0$. To better understand the dynamics of this model, I have also plotted the depletion rate for different values of the time index (see Figure 2.15). The figure displays with dark lines (one full line, and one dotted line), the trajectory of two imaginary countries that start with equal levels of income per capita (USD (1987) 700) and depletion rates (7% of GDP).

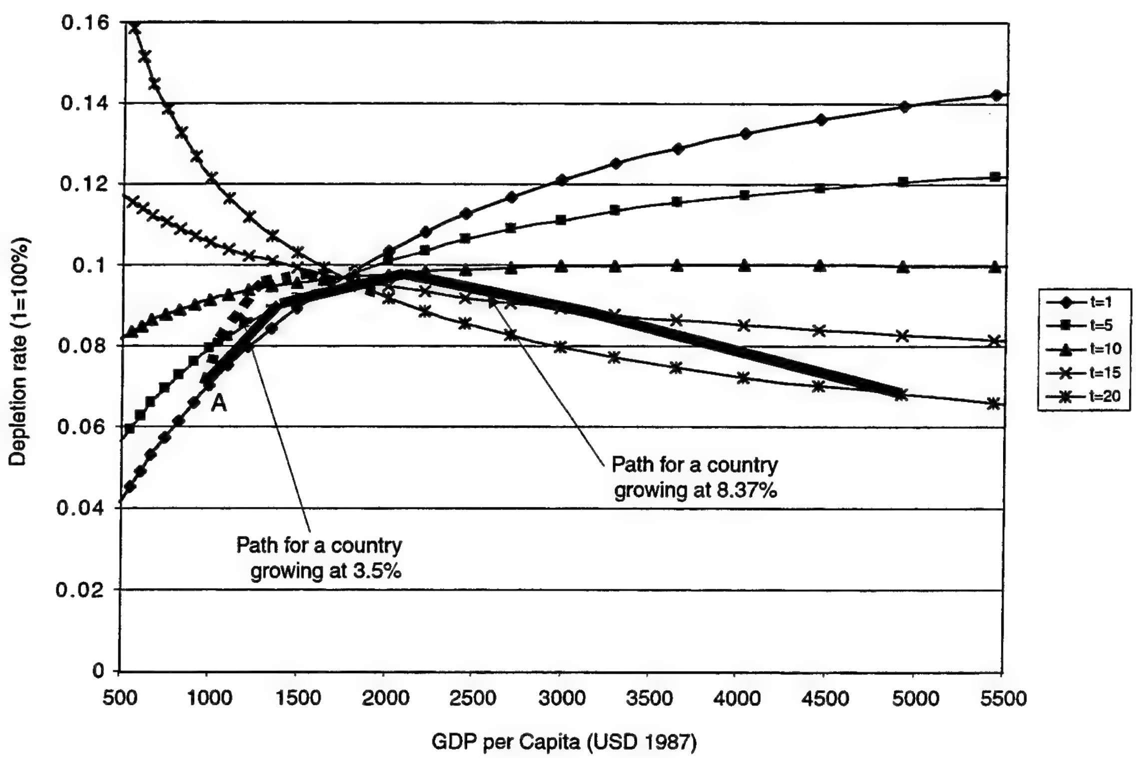

Figure 2.15: Depletion Rate as a Function of GDP per Capita (Time Effects Model).

Source: Author calculations.

The first country grows at 3.5% per year, and within a period of 20 years reaches a per capita income of close to USD (1987) 2,000. During the first fifteen years its depletion rate increases up to 10% of GDP and then declines slowly to 9%. The other country, by growing faster, at 8.3%, is able to reach a level of income per capita of USD (1987) 5,000. Its depletion rate originally increases to 10% but then falls below 8% of GDP. We observe that in this second model, the increase in the depletion rate for low levels of development is sharper than in the previous model. The decline, on the other hand, is slower. Also, the inflection point varies depending on the growth rate.

Both models, however, confirm the hypothesis that depletion rates increase at lower levels of economic development, and tend to decrease at higher levels of development. The cut-off takes place at levels of income close to USD (1987) 1,000. Both models, unfortunately, hide the real sources of change in depletion rates. Hence, in the next section, I study models that take a closer look at the structural determinants of depletion rates.

5.2 Structural Change, Social Capital, and Depletion Rates

We have shown that depletion rates are intimately related to the level of economic development. The questions that remain to be answered are: a) what are the factors that change when economic development takes place, and that affect depletion rates; and b) are there factors that, while not correlated with the level of economic development, are important determinants of depletion rates. Factors that undoubtedly change as economic development takes place are the sectorial composition of the economy, and the legal and institutional frameworks that regulate the use of natural resources and environmental services. However, other factors such as the absorption capacity of new technologies or the type of international financial commitments that a given country has to meet, are not necessarily directly linked to the level of economic development, and yet may also influence depletion rates.

In this section, I use the panel data set to explain international variations in depletions rates. A first question that I address is what is the role of each economic sector in explaining international differences in depletion rates. The second question is related to policy changes. I have suggested that during the past two decades, countries have had a tendency to move to economies based on market signals that may have eliminated distortions in the market for natural resources. Unfortunately, we do not have specific measures for these changes. Also, we do not observe indicators, such as country level prices for natural resources that could be used as proxies for the level of regulation. Nonetheless, it is reasonable to expect that the ability of countries to implement sound environmental policies will be related to the form and strength of their institutions (see North, 1990). For example, we may expect that in countries with consolidated democratic systems where individuals enjoy broad political and civic rights, social organizations that lobby for environmental protection are more likely to emerge. Therefore, we can use indicators for the level of political and civil rights as proxies for the likelihood that a given country will implement sound environmental policies.

A third idea that I address is related to the role of the structural dimension of social capital, that is the degree of network connectivity that exists within a given country. Indeed, the ability of developing countries to reduce depletion rates depends in part on their ability to choose production technologies with lower environmental damages. For example, policies that eliminate price distortions in the market for natural resources will be more effective (e.g., will have less negative impact on economic growth) when alternative production technologies - less intensive in natural resources and environmental services - are available as substitutes for old technologies. By affecting information flows and the extent to which cooperative behavior emerges, business and social networks play an important role in determining the absorption capacity for new technologies in the economy (see Chapter 4). Hence, we may expect that other things being equal, more interconnected societies will tend to have lower depletion rates. The strength of the financial sector is also an important enabler for the diffusion of new technologies. A well functioning and competitive financial sector is likely

to reduce credit constraints, and supply the financial resources required to finance investments in new technologies.

A fourth idea, that has received little or no attention, is the role of external financial constraints. During the '70s, developing countries increased their public and private foreign debt dramatically. Different factors explain this phenomena, such as the over supply of oil-related dollars in the international financial system (see Little et al., 1993; and Krugman, 1999 for other arguments). Regardless of whether creditors were being rational when they lent the money, the fact is that as in the case of natural resources, too often the new financial resources coming from abroad were not invested in projects with adequate rates of return. In many cases, governments use these resources to provide subsidized credits to private companies that deposited back their loans in foreign banks where they received market interest rates. The debt crisis initiated with the Mexican moratorium in 1982 reflected developing countries' incapacity to generate the resources necessary to comply with creditors' obligations. Since then, many developing countries have been trying to equilibrate their external accounts through policies aiming to stimulate the development of the exports sector. Very often, these strategies have resulted in an over-exploitation of the natural resource base (see for example the case of the mining sector in Mexico in Robalino and Treverton, 1997). This being the case, one may expect that other things being equal, countries with a higher burden of payments to service foreign debt will also tend to have higher depletion rates.

In summary, I hypothesize that there are seven factors that explain international variations in depletion rates: 1) the sectorial composition of the economy; 2) the external financial pressure facing the country; 3) the degree of development of the financial sector; 4) the level of development of the country; 5) international technological progress; 6) the degree of institutional strength; and 7) network structures. Given little theoretical guidance in terms of the type of model specification that one should use, I have opted for estimating reduced form models. Therefore, I express the depletion rate of a country i at time t by:

$$\log\left(\frac{d_{it}}{1-d_{it}}\right)=\beta_0+\beta_j\sum_{j=1}^{3}s_{jt}+\beta_4 FDX_{it}+\beta_5 M3_{it}+\beta_6 y_{it}+\beta_7 x_{it}+\beta_8 t+\mathbf{I}_{it}\gamma+\mathbf{NW}_{it}\iota+\varphi_k\sum_k reg_k \quad (2.8)$$

where s_j represents the share of economic sector $j\in$ {1=industry, 2=manufacture, and 3=services} (agriculture appears as the reference sector); FDX is the share of foreign debt payments in total exports revenues (our indicator of international financial pressures), M3 represents money and quasi-money as a share of GDP (our proxy for the "size" of the financial system), y is the GDP per capita, t is a time index (our proxy for international technological progress), **I** is a vector with proxies for institutional strength, NW is a vector with proxies for networks' structures; and **reg** are regions dummy variables used to estimate (2.8) as a fixed effects models.

I have estimated several models like (2.8) that differ in the types of institutional indicators and proxies for networks structures considered, as well as the inclusion or exclusion of GDP per capita. In the case of institutional indicators, I have worked with two proxies: the index of civil liberties (*civLib*) and the index of political rights (*polRight*). These are subjective indicators that measure attributes such as the meaningfulness of elections, firmness of election laws and campaign opportunities, voting power, political competition, or freedom from external or military control. The validity of these indicators is analyzed in depth in Fedderke and Klitgaard (1998), and Klitgaard and Fedderke (1995). I have also used two proxies for networks' structures: Kedzie's indicator (1997) of social connectivity (*conect*) and Fedderke and Klitgaard (1998) indicators of Ethno-Linguistic Fractionalization (*avelf*) (see Fedderke and Klitgaard, 1998, for an interpretation of these indicators). The former is constructed on the basis of indicators such as information regarding the number of phone lines per capita, and internet nodes per capita. The latter is the average of three indicators of Ethno-Linguistic Fractionalization (Muller, Roberts, and Gunnemark 1 and 2) described in Easterly and Levine (1997). These indicators measure the probability that two individuals picked at random belong to different ethnic groups.

In Table 2.4, I report the results of four models that are able to explain up to 50% of the international variance of depletion rates. One can confidently (i.e., independently of model specifications) derive three clear messages from these results. First, the sectorial composition of the economy is, as expected, an important explanatory factor of depletion rates. A one percentage point increase in the share of the industrial sector (e.g., from 30% to 31%) with an equal reduction in the agriculture sector, appears to increase the depletion rate by 1.8 percentage points (e.g., from 10% to 11.8%). On the other hand, the manufacture and services sectors reduce depletion rates, although their effects are less important (a 1% expansion of these sectors relative to the agricultural sector reduces depletion rates between 0.1 and 0.8 percentage points). Hence, observed increases in depletion rates in early stages of development are mostly explained by increases in the share of the industrial sector.

Second, the burden of foreign debt appears to be positively related to depletion rates. Hence, a 10 percentage points increase in the share of foreign debt reimbursements in total exports, is associated with an increase in depletion rates of 1.2 percentage points (i.e., from 10% to 11.2%). There are two interpretations of this result. The first is that originally, more loans where given to countries with high depletion rates. In other words the debt burden is an endogenous variable that depends on the depletion rate. A counter argument is that current levels of foreign debt are already the products of renegotiations that are more or less independent of depletion rates (e.g., Plan Brady). Also, if the foreign debt depends on depletion rates, our indicator of the debt burden should be correlated with past depletion rates and not with current depletion rates. Therefore, a second interpretation of the econometric result is simply that as the burden of foreign debt increases, countries may feel more pressure to deplete their natural resources in order to comply with foreign creditors. An implication is that in the case of highly indebted countries, stabilization of depletion rates may require external debt renegotiation.

The third message is that time and the level of economic development remain important drivers of reductions in depletion rates. These two variables are very likely to account for increases in the levels of education of the

population and technological progress, but also for changes in dominant ideologies (e.g., the movement to free market reforms observed during the '80s and '90s).

Model	1			2			3			4		
Prob > F	0			0			0			0		
Adj R-squared	0.5682			0.5738			0.5881			0.5942		
oddD	Coef.	Std. Err.	P>|t|	Coef.	Std. Err.	P>|t|	Coef.	Std. Err.	P>|t|	Coef.	Std. Err.	P>|t|
x_GDP	0.0007857	0.002995	0.793	-0.0078264	0.0038227	0.041	-0.0044613	0.0038165	0.243	-0.00251	0.003832	0.512
ind_GDP	0.1208571	0.0043467	0	0.1271688	0.0064511	0	0.1253318	0.0064662	0	0.126328	0.006402	0
ser_GDP	-0.0171082	0.004473	0	-0.0178253	0.0057012	0.002	-0.0211211	0.0057093	0	-0.01504	0.005715	0.009
man_GDP	-0.0896858	0.0064987	0	-0.0970719	0.0080381	0	-0.0854648	0.0089145	0	-0.0895	0.008261	0
debtX	0.0146562	0.002415	0	0.0114817	0.0028325	0	0.0085075	0.0028549	0.003	0.007714	0.002864	0.007
t	-0.0133241	0.0055846	0.017	-0.0186217	0.0086656	0.032	-0.0201098	0.0085309	0.019	-0.02022	0.008457	0.017
avelf	-0.977997	0.1613533	0	-0.785394	0.1835652	0	-0.7320819	0.1874333	0	-2.83963	0.599586	0
m3_GDP	-0.0016609	0.0028657	0.562	0.0081765	0.0034555	0.018	0.0092862	0.0034849	0.008	0.008365	0.003469	0.016
GDP_Cap				-0.0001176	0.0000391	0.003	-0.0000876	0.0000417	0.036	-0.00015	4.08E-05	0
civLib							-0.5121193	0.1042416	0	-0.19658	0.046007	0
polRight				-0.0788116	0.0333522	0.018	0.2866035	0.0852589	0.001			
conect				-0.0385687	0.023301	0.098	-0.0817727	0.0243374	0.001	-0.22802	0.055771	0
cam	-0.1227767	0.1753826	0.484	0.0056682	0.2167611	0.979	0.0782991	0.2453548	0.75	-0.1287	0.260596	0.622
car	(dropped)			(dropped)			(dropped)			(dropped)		
eap	1.11504	0.1632198	0	0.6920703	0.2045465	0.001	0.791264	0.2470214	0.001	1.002829	0.238859	0
me	0.0978587	0.3761324	0.795	-0.734191	0.4498538	0.103	-0.4531443	0.446114	0.31	-0.78573	0.449534	0.081
naf	0.5217179	0.1604092	0.001	-0.0695301	0.2143826	0.746	0.26458	0.2389552	0.269	0.375265	0.237096	0.114
nam	1.821486	0.2745594	0	2.075112	0.2882591	0	2.394343	0.3385507	0	2.822425	0.3413	0
sas	1.374878	0.1509666	0	0.6910717	0.1865319	0	1.048106	0.2174532	0	0.994153	0.221223	0
ssa	0.5390574	0.1342037	0	0.2760482	0.1747721	0.115	0.5983329	0.2271102	0.009	0.493068	0.227419	0.03
we	-0.2075907	0.2385706	0.384	-0.4791043	0.2732899	0.08	0.2544021	0.3211936	0.429	0.304912	0.316196	0.335
sam							0.3101168	0.2091904	0.139	0.554093	0.2054	0.007
avelf2										2.678043	0.708754	0
conect2			.							0.01751	0.005706	0.002
_cons	-4.643449	0.2655014	0	-3.604942	0.4168425	0	-3.246368	0.4340269	0	-3.16776	0.438617	0

Table 2.4: Structural Determinants of Depletion Rates.

Source: Author calculations.

Geographic location also explains differences in depletion rates. Sub-Saharan Africa, South America, Mexico, South Asia, and East Asia and Pacific tend to have higher depletion rates than high-income OECD countries. Since the model controls for the share of the different economic sectors, proxies for initial endowments, one possible interpretation for these results is differences in climate and culture.

Regarding the role of the financial sector (proxied by the extended measure of money supply, M3) the results are inconclusive. This indicator was supposed to be a proxy for a country's new technologies absorption capacity. When GDP per capita is not introduced in the model, this variable appears to contribute to a reduction in depletion rates. However, when we include GDP per capita, M3 appears to increase depletion rates. One is then tempted to conclude that, other things being equal, dynamic financial sectors tend to evolve in countries with higher depletion rates. One can in part explain the phenomena by noticing that countries with emerging financial markets tend to be countries that are attractive to foreign investors. Probably one of the reasons why these countries are interesting is lax environmental policies that facilitate the exploitation of natural resources (see the case of Mexico in Robalino and Treverton, 1997).

In the case of the institutional indicators, the results also need to be interpreted with caution. Both the civil rights indicator and the political rights indicators have a negative sign when used independently. Hence, an increase in any of these indicators tends to be associated with lower depletion rates. However, when both indicators are used together, increases in civil rights reduce depletion rates while increases in political rights increase depletion rates. This change in sign could simply indicate correlation between the two institutional indicators. However, this correlation is less than 0.3. An alternative explanation is that the civil rights indicator becomes a proxy for the ability of economically weak social groups to lobby for environmental protection. Thus, Governments may be less likely to fail to implement policies that guarantee an adequate management of

natural resources, in order to satisfy the interest of particular commercial power centers. For example, in Ecuador, the Shuaras Indians in the Amazon region were able to stop the concession of a new oil field to the multinational Texaco. They have also put pressure on Texaco to reimburse environmental damages associated with the exploitation of oil fields in the region. On the other hand, the political rights index is measuring the degree of political competition. The results suggest that as competition increases, it becomes more difficult to coordinate the implementation of environmental policies that tend to reduce depletion rates.

In Table 2.4, the first three model specifications provide mixed evidence regarding the role of networks connectivity. As expected, the indicator *conect* has a negative sign, suggesting that in more interconnected societies coordination can facilitate not only the implementation of environmental policies but also the adoption of low environmental damaging technologies. The Ethno-Linguistic Fractionalization (ELF) index, however, tells an unexpected story: that as fractionalization increases, depletion rates *decrease*. One possible interpretation is that fractionalization is acting against the diffusion of technologies that have high environmental impacts. For example, fractionalization may impede the development of the industrial sector. A more interesting story, however, is that both connectivity and fractionalization are non-linearly related to the depletion rates. The fourth model specification in Table 2.4 provides strong support for this view. Indeed, both squared terms are positive and significant, while the non-squared terms are negative. For example, at low levels of Ethno-Linguistic Fractionalization, increases in the index reduce depletion rates. Given that 30% of our sample falls in the first and fifth quintile of the ELF distribution, one can interpret this result by saying that some degree of diversity is "socially optimal" (see Page, 1999). However, after some threshold, higher fractionalization is accompanied with higher depletion rates, meaning that coordination for technology adoption or policy implementation becomes more difficult. A similar story would hold with the connectivity indicator. At low levels of connectivity, higher connectivity reduces depletion rates. However, at high levels of connectivity, further increases may increase depletion rates, due to inertia or also coordination failures. To illustrate these results, I have plotted in Figure 2.16 the

marginal effect of changes in the Ethno-Linguistic Fractionalization index and the connectivity index.

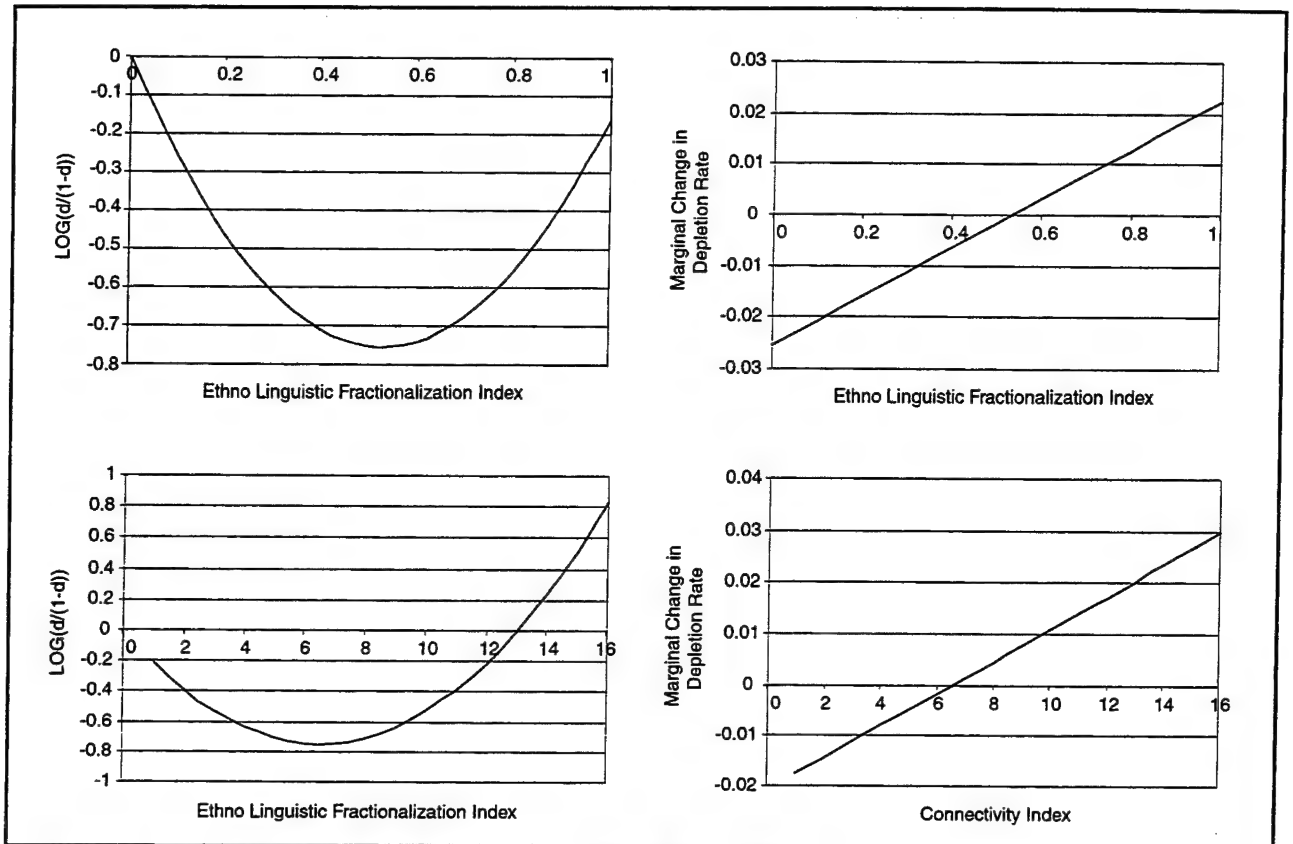

Figure 2.16: Network Structures and Depletion Rates.

Source: Author calculations.

The figures have been drawn *within* the range of variation of these indexes in the estimation sample. Hence, the ELF index ranges between 0 and 1, while the connectivity index ranges between 1 and 16. I assume that the reference depletion rate is set at 0.10 (10% of GDP). We observe that an increase of the ELF index from 0.2 to 0.3 decreases depletion rates by 1.5 percentage points (i.e., from 10% to 8.5%). However, an increase of ELF from 0.8 to 0.9 increases depletion rates from 10% to 11.5%. Similarly, in the case of the connectivity index, an increase from 2 to 3 reduces depletion rates from 10% to 9%. An increase in this index from 14 to 15 increases depletion rates from 10% to 12%.

5.3 Do Depletion Rates Converge?

Besides being indicators of sustainability, depletion rates are indicators of the degree of nations' dependence on their natural resource base. The question that I want to address is whether we are witnessing the creation of a multi-polar world where some countries specialize in the production of natural inputs (these economies will be relatively intensive in natural resources); while others specialize in the production of outputs. High depletion rates do not necessarily imply unsustainability. Indeed, countries with a large natural resource base may enjoy the possibility of high extraction rates. Nonetheless, in the long run, this type of specialization may tend to be associated with lower labor productivity, and hence lower income per capita (see Sachs and Warner, 1996).

There is no strong theoretical reason to believe that countries should converge to similar depletion rates. As shown in the previous section, differences in depletion rates are in part explained by structural differences. If countries converge to some steady state, the depletion rate should differ in relation to these structural factors.

The question of convergence in depletion rates is similar to the question of convergence in income per capita. Several empirical and theoretical studies have addressed the issue (see Durlauf, 1996; Sala-i-Martin, 1996; Bernard and Jones, 1996; Quah, 1996; and Galor, 1996) of whether income per capita tends to equalize. The majority of studies analyze convergence in one of two forms: countries converging to the same steady state; or countries converging to different steady states, depending on initial conditions and policies. Using different samples, studies have provided evidence for one or the other of the forms of convergence (see Barro, 1997 for a review). However, in recent years, seminal work by Quah (1992) demonstrated that the econometric methods used to test the convergence hypothesis were in most cases inappropriate. Indeed, the standard method was to compute an average growth rate for a given period of time, and then regress this rate on the initial level of income per capita and other controls (mostly proxies for initial conditions). A negative coefficient on the initial level of income per capita implies that,

controlling for initial conditions, growth rates are higher for low income countries and these will therefore tend to catch up with high income countries. Notice that this result does not necessarily imply that they will converge to the same level of income per capita of developed countries. Indeed, because the initial conditions differ, the steady states differ. However, given these initial conditions, each steady state is unique. Quah's argument to demonstrate the inappropriateness of the method is the following. Imagine that the convergence hypothesis is true. Then with a sufficiently long time series, the sample average growth rates for different economies all converge in probability to the same underlying number (this is simply the law of large numbers for the growth rate: it applies regardless of whether incomes are individually difference stationary or trend stationary). On the other hand, initial conditions have some distribution and are independent of the length of the sample period. Thus, any correlation estimator between average growth rates and initial conditions will converge to zero with probability one. This will happen precisely when the convergence hypothesis is true. But, if one applies the methods, this zero correlation will be evidence against the convergence hypothesis: therein lies a contradiction.

Quah suggests a novel alternative (see Quah, 1992). He sets the null hypothesis by stating: "the income disparity across any two economies is a zero drift integrated process". Then, there is convergence if this hypothesis can be rejected in favor of stationarity. When the income of two countries are integrated, the income disparity is stationary if and only if the bivariate income process has a co-integrating vector (1,-1). Thus, if we are only interested in two economies, standard methods to test for co-integration could be used. It is clear however, that co-integration between two countries is irrelevant for the convergence hypothesis. Unfortunately, once the sample of countries increases, the problem becomes intractable with standard time series methods, since one would be forced to take into account a large number of cross-country income covariances. The method used by Quah incorporates concepts from statistical mechanics into classical econometrics. I will describe the method in relation to my application.

I am interested in testing whether depletion rates across countries tend to converge. These depletion rates are observed for a set of N countries and T

time periods. Thus by fixing some country z as a benchmark, I can define relative depletion rates by:

$$\tilde{d}_{it} = d_{it} - d_{zt}, \tag{2.9}$$

Instead of treating $\tilde{d}_{it}$ as a panel, following Quah, I treat it as a *random field*. This random field is more precisely a collection of random variables in a two dimensional lattice Z={(i,t)|i,t are integers}. Before any type of statistical analysis can be done, it is necessary to model the possible dependence and heterogeneity across vertices in the lattice (i.e., observations). The assumption that observations are independent and identically distributed is a benchmark in econometrics. However, this assumption is clearly inappropriate in this case. Indeed, we know that countries "move together" and that they are heterogeneous. The alternative is to define a probability space over the lattice that provides the probability distribution of each subset of vertices as a function of the states of other vertices. Given that this method is relatively new in econometrics, its detailed discussion has been reserved to Appendix 8.3. Here, it is sufficient to state the following theorem due to Quah (1992):

Suppose that $\{\tilde{d}_{it}\}$ is generated by:

a) $\tilde{d}_{it} = \beta_0 \tilde{d}_{it-1} + \mu_{it}$, $i = 1,\ldots,N; t \geq 1$;

b) $\beta_0 = 1$

c) $\tilde{d}_{i0}, u_{it}$ satisfy "basic assumptions" (see Appendix 8.3),

then the vector: $\beta_N = \dfrac{\sum_{i=1}^{N}\sum_{t=1}^{T}\tilde{d}_{it}\tilde{d}_{it-1}}{\sum_{i=1}^{N}\sum_{t=1}^{T}\tilde{d}^2_{it-1}}$ verifies:

$\beta_N \xrightarrow{\Pr} 1$ *as* $N \to \infty$. Furthermore, its distribution is normal[5]. Intuitively, what the estimator is doing is taking a country as a reference, and estimating the standard time series model or all the other countries. So, given a reference country, the indicator computes whether on average other countries converge to the reference country. If all countries on average converge to all

countries, independently of which country is chosen as the reference, the β_N will be less than 1. Hence, if we take the average of all β_N across all reference countries, we should get a number less than one. However, if there are countries from which on average other countries diverge, the average of the β_N 's may be greater than one.

The previous theorem basically states that under our set of assumptions, β_N can be treated as a random variable with known distribution. The hypothesis that I want to test is whether β_N is statistically different from one. Because the estimator is normally distributed, the standard t-test can be applied (this is in contrast to the standard time series estimator of the first order integrated process, where adjustments to the probability distribution are required; see Dickey and Fuller, 1981; and Phillips, 1987).

There is no standard statistical package that can be used to estimate β_N. However, the implementation of the estimator is straightforward. My results are better illustrated by Figure 2.17.

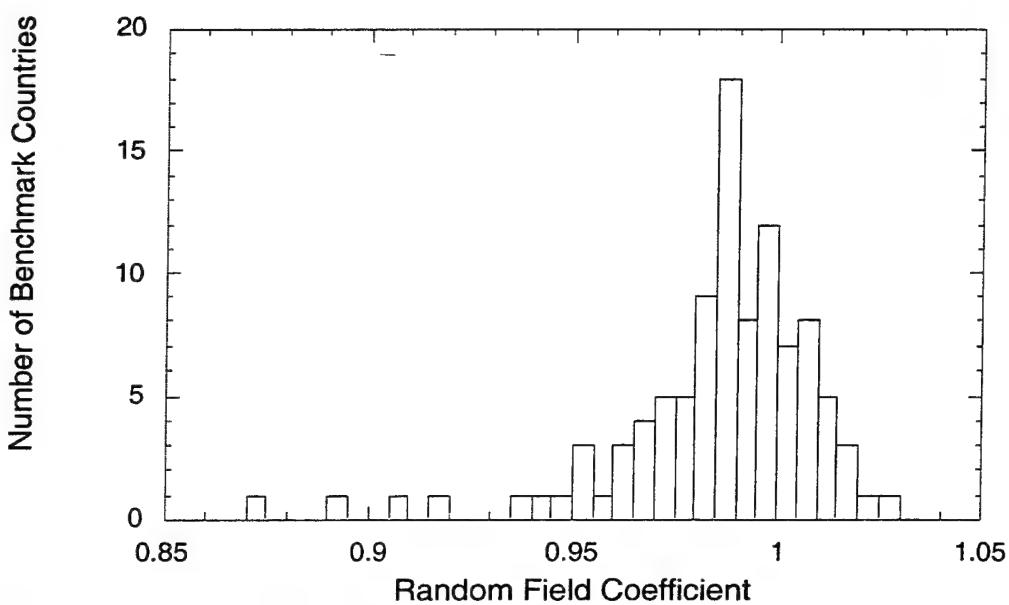

Figure 2.17: Distribution of the Convergence Parameter.

Source: Author calculations.

The figure provides the distribution of β_N, where each realization corresponds to the selection of a benchmark country. The conclusion is straightforward: the estimated coefficient is not likely to be significantly different from one. Indeed the t value for the test H0: $\beta_N - 1 = 0$, is 0.575. Hence, I cannot reject the null hypothesis and have to conclude that depletion rates across countries tend to diverge. Notice that I have not made any assumptions regarding structural homogeneity or heterogeneity across countries. Countries may be diverging simply because they are structurally different. Alternatively, divergence may be the result of the vagaries of history. Which is the actual reason does not matter here. Our only goal is to provide robust empirical evidence of whether countries converge or not.

However, the previous result needs to be interpreted with caution. Indeed, in the analysis of Sub-section 5.1, I showed that at initial levels of development, countries tend to increase depletion rates. Hence if we compare a low income and a high income country, it is likely that their depletion rates will be diverging, yet it does not mean that they will not start to converge after the first country has reached some level of development.

To correct for this bias, I have repeated the analysis by income groups, using high income countries as reference. The results are presented in Figure 2.18. While low income countries include countries with income per capita lower than USD 1,000, the other categories have countries with more than USD 1,000 per capita. Our analysis in Sub-section 5.1 suggests that these countries should have started to reduce depletion rates. Yet, we observe that within the low-middle income group, we are likely to observe countries such as Iran with depletion rates that diverge from the group. The same is true for some countries within the middle-high income group, such as Bahrain.

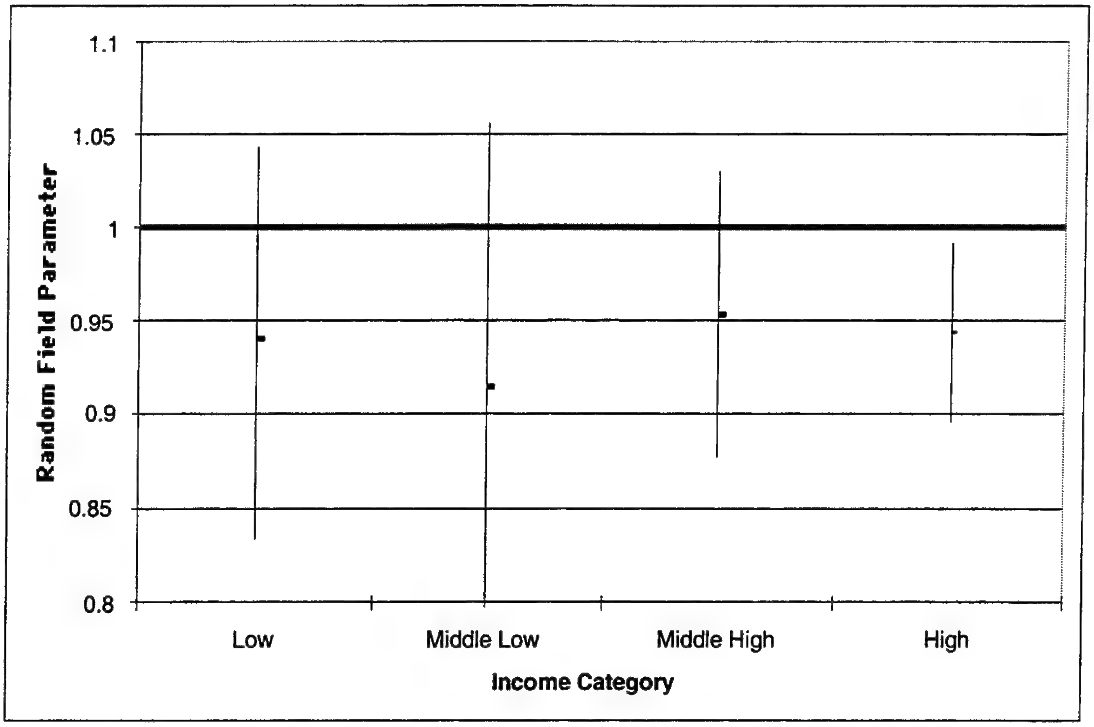

Figure 2.18: 95% Confidence Interval for Convergence Coefficient by Income Group.

Source: Author calculations.

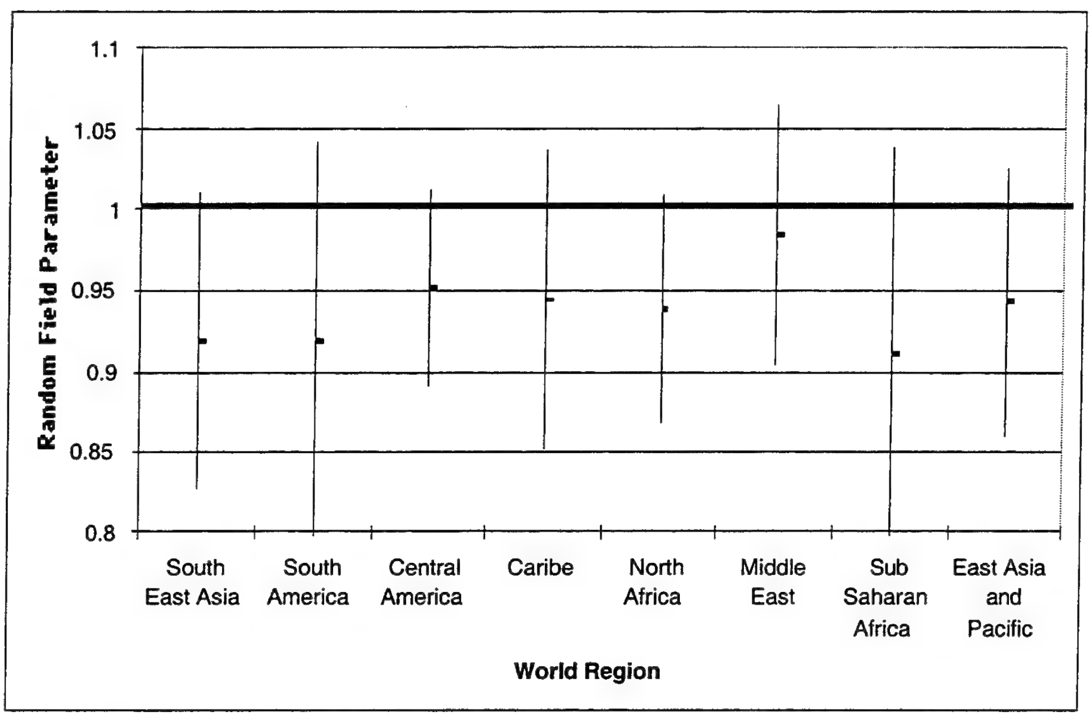

Figure 2.19: 95% Confidence Interval for Convergence Coefficient by Region.

Source: Author calculations.

In Figure 2.19, I have repeated the analysis for different regions of the world, taking in all cases OECD countries as the reference. The message is that some regions of the world are more likely to converge to OECD levels than others. South East Asia and North Africa fall into this category. However, for South America, Caribbean, Middle East, and South Africa, countries are more likely to diverge.

These results present some empirical evidence to suggest the idea of the formation of a multipolar world with countries with high depletion rates that specialize in the production of natural inputs for the production process, and countries with low depletion rates that specialize in processing these natural inputs. High depletion rates do not necessarily imply that a country is outside a sustainable path. Indeed, the optimal growth path may imply high depletion rates, as long as the rent from exploitation of the natural resources is invested efficiently. However, in the long run, sustainability may require stabilization of the stock of natural resources (the stock of non-renewable resources cannot last forever). This inevitably implies reducing depletion rates. For those countries that have higher depletion rates this stabilization process may turn out be more difficult. Thus, these countries should receive most of the attention of international organizations.

6. Conclusion

This chapter focussed on the definition and measurement of sustainable growth, as well as an empirical analysis of the determinants of the dynamics of depletion rates. In the first part of the chapter, I suggested that key indicators (i.e., flags) of sustainability are the stock of natural, produced, and human capital and their respective net investment rates. Thus, a sustainable growth path can be assessed in terms of extended genuine savings, defined as the traditional savings minus the depreciation of produced capital and the stock of natural resources, plus investments in education and health. Sustainability in the long run will depend on developing countries' ability to increase investments in human and produced capital, and stabilize their stock of natural resources.

In a second part of the chapter, I studied the determinants of depletion rates. The data provide evidence that in the first stages of economic development, countries tend to increase depletion rates but that as economic growth takes place, these depletion rates tend to diminish. The transition point appears to be close to USD (1987) 1,000 per capita. The data also suggests that institutions and social network structures are important determinants of the dynamics of depletion rates. In particular, depletion rates tend to be higher in countries with low political and civil rights, and in countries with low or very high levels of social capital. I also provided some evidence that the external financial constraint imposes pressures on developing countries to increase their depletion rates. Finally, the data supports the idea of a multi-polar world where some countries remain highly dependent on their natural resources base.

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[1] Lately, it has been suggested that another form of capital, social capital, should also be incorporated in nations' wealth. I have postponed the discussion of this issue to Chapter 5.

[2] The true social cost of a unit of natural resource is its marginal production cost. If this cost can be represented by a function mc(q) where q is the level of output, then the total social cost of production is given by: $\int_0^q mc(q)dq$.

Yet, in the World Bank calculations, this cost is implicitly given by: mc(q).q + Fixed Costs. Hence, profits over estimate producer surplus.

[3] The reader can argue that if d is high and environmental damages are high, then D>Q and d>1. However, these damages are not likely to be registered in Q (GDP from the standard national accounts). As a matter of fact, in our panel data set we always have 0<d<1.

[4] Other specification could have been used. For example, time effects that vary discontinuously with the level of GDP per capita (e.g., low, middle, high). However, defining these thresholds is rather an arbitrary operation. Thus, I have chosen to work with continuous time effects.

[5] The estimator of the random field coefficient is different from the standard time series estimator given by

$$\hat{\beta} = \frac{\sum_t \tilde{d}_t \tilde{d}_{t-1}}{\sum_t \tilde{d}_{t-1}^2}.$$

Chapter 3 - Technology Diffusion and Social Capital

1. Introduction

In the previous chapter I argued that the likelihood of a given country converging to a sustainable growth path (even in the weak sense) depends on its ability to stabilize the stock of natural resources. Such stabilization can only occur if depletion rates are reduced. Reductions can result from less economic activity - not an option for countries with a pressing need to increase standards of living - or from a transformation of the productive structure. This transformation needs to take place not only in terms of the sectorial composition of the economy, but also in terms of the type of production technologies used within each economic sector. Sustainability requires technologies with high productivity and low environmental damages.

Recently, RAND published a study showing how different mixes of energy technologies in the developing world have different effects on long term growth (see Bernstein et al., 1999). Researchers showed that the net benefits of technology mixes dominated by renewable energy technologies were in the order of 5% to 10% of GDP. However, technology mixes were constructed exogenously in the study. The question that researchers were trying to answer is what are the differences in the present value of GDP of using alternate technology mixes. Having an estimate of these differences is valuable in itself. However, it is as important to know what are the types of mixes that are more likely to prevail - given producers' technology choices - and how the government could try to influence final outcomes. The answer to these questions requires a methodological framework to model the technology diffusion process. The main goal of this chapter is to initiate the development of such a framework.

An assumption of technology diffusion models is that choices are related to expected costs and benefits. The complication derives from trying to formalize the process that defines these expectations. A first goal of this chapter is to show that these expectations, and therefore the process of technology diffusion, are intimately related to the concept of social capital.

Roughly speaking, social capital is treated as the set of social networks and institutions within a given economy that shape individuals' interactions. Considering these interactions in the design of technology policies will turn out to be very important. The second goal of the chapter is to introduce a series of mathematical concepts from statistical mechanics and potential games, that will be useful to represent the social interactions within a formal model.

The chapter is organized into five sections. Section 2 concerns the process of technology diffusion. I review the literature on theoretical models of technology diffusion and identify features that one should incorporate in the analysis of technology policies. Section 3 introduces the concept of social capital. I summarize the current literature on definitions, roles and measures of social capital. Then I discuss how social capital is treated in this research, and how it relates to the process of technology diffusion. Section 4 describes three models of social interactions from the recent literature on statistical mechanics and potential games. I illustrate how insights from these simple models can be used when constructing an applied model of growth where the effect of social capital and social interactions in policy choices can be studied. In Section 5 I start the construction of such a model with the design of a simplified prototype that is more amenable for mathematical analysis. I use this prototype to characterize some properties of the model dynamics. I show that these dynamics are non-ergodic and that the probability of convergence to a socially optimal path is related, non-linearly, to the type of network typology.

2. The Process of Technology Diffusion

Traditionally, the process of technological change has been viewed as an aggregation of three sub-processes: invention, innovation, and diffusion (see Sahal, 1981). The focus of this research is on the latter. The main rationale for ignoring the first two sub-processes is that in the short and medium terms, technological change in most developing countries will mainly result from their ability to adopt technologies designed and implemented by developed countries, and not by their ability to invent or innovate (see Kemp et al., 1994).

Much of the literature on technological change deals with invention and innovation. Too often, it is assumed that once new processes or products become available as a result of invention and innovation, the market will guarantee their diffusion, if the processes or products in question are efficient from an economic point of view. Unfortunately, this is not always the case. The process of technological diffusion is far more complex, and diffusion externalities may be pervasive.

2.1 The Contagion Model

The seminal work on technology diffusion is usually attributed to Mansfield (1961), although his approach was also employed by Griliches (1957). Mansfield studied the American iron, steel, coal, rail, and brewing industries. He showed that the process of technology diffusion could be modeled by a contagion model for which the differential equation had the logistic function as the solution (for a modern treatment of Mansfield's model, see Lizardo de Araujo, 1995). This function leads to the well known S shaped diffusion curve that relates number of adopters of a given product or its market share to time. We have:

$$s_t = \frac{e^{\alpha_0 + \alpha_1 t}}{1 - e^{\alpha_0 + \alpha_1 t}} \qquad (3.1)$$

where s_t is the market share of a given technology or product at time t, and α_0 and α_1 are parameters to be estimated. By taking the inverse, subtracting 1, and taking the inverse again, we get:

$$\frac{s_t}{1 - s_t} = e^{\alpha_0 + \alpha_1 t} \qquad (3.2)$$

Hence, if one observes market shares for a given product or technology over time, the following log-linear function can be estimated:

$$\log\left(\frac{s_t}{1-s_t}\right) = \alpha_0 + \alpha_1 t \tag{3.3}$$

Notice that when the market share is 50%, then $\alpha_0 + \alpha_1 t = 0$. Hence $t = \dfrac{-\alpha_0}{\alpha_1}$ is the number of years required by the technology to hit 50% of the market.

This type of black-box approach was driven by the need to replicate the empirical observation that the adoption of new processes or products was not an instantaneous mechanism. Hence, diffusion resulted mainly from changes in the expected profitability of the adoption and the progressive dissemination of information about its technical, and economic characteristics. In this tradition, diffusion can be viewed as the transition between two "classical" long-term equilibrium positions (see Metcalfe and Gibbons, 1988).

2.2 Equilibrium Diffusion Models

Further empirical investigation confirmed the role of profitability in adoption decisions (see Davies, 1979; Nabseth and Ray, 1974; and Gold, 1981). However, the same research also depicted the importance of firms' heterogeneity in the diffusion process. Indeed, different firms having different production functions derive different utilities from alternative technologies. This implies the existence of a distribution of reservation prices below which firms will adopt the new technology. Under the assumption that the price of new technologies diminishes as the number of users increases, diffusion results from a decline in price along the reservation price distribution. This idea was formalized in a second generation of diffusion models that Silverberg, Dosi, and Orsenigo (1988) label "equilibrium diffusion models". Here, diffusion can be viewed as a sequence of equilibria determined by changes in the characteristics of the technology and the environment. Research in this tradition (see Stoneman and Ireland, 1983; David and Olsen, 1984; and Reinganum, 1981) shows the importance of agents' heterogeneity, agents' technological expectations, and the interactions

between suppliers of new technologies and potential adopters. For example, as I discuss in Chapter 4, strategic behavior on the part of the producers of new technologies facing a competitive market may lead to diffusion rates that are too fast from a social point of view (see Stoneman and Diederen, 1994). This approach has inspired the applied models of technology diffusion that I describe in Chapter 5.

The models in the "equilibrium tradition" share three features. First, they assume that agents adopting technologies have either perfect information or, when facing uncertainty, have perfect knowledge of the probability distributions of the concerned random variables. Second, most of the analysis is made in terms of the existence of a technological equilibrium, and little is said about the adjustment process between equilibria. Third, the analysis assumes representative firms or consumers. Hence, when heterogeneity is introduced, it is usually limited to two types of consumers or firms.

2.3 The Evolutionary Approach

A third approach, labeled the evolutionary approach, relaxes assumptions about perfect rationality and introduces the concept of radical uncertainty. This approach, initiated by Nelson (1968) and Nelson and Winter (1982), has led a to a rich literature now associated with the works of Silverberg (1984), Silverberg et al. (1988), Metcalfe (1985), and Teitelbaum and Dowlatabadi (1998). The main methodological innovation in this approach is the introduction of agent-based models instead of the standard representative firm or consumer model. The evolutionary approach incorporates the main characteristics of "equilibrium models", such as imperfect information and heterogeneity, that have proven to be important in empirical studies. However, the dynamic analysis is based on a disequilibrium framework. Hence, firms do not make adoption decisions by solving a given intertemporal maximization problem on the basis of expectations about costs and benefits, but rather act on the basis of a finite set of rules that they update by trial and error. Also, resulting choices at a given point in time are not constrained to generate an equilibrium state where supply of factors is equal to demand. The

evolutionary approach can be thought of as inspired by a combination of both the Shumpeterian and Darwinian traditions. Shumpeter is the source of the random character of technological innovations within these models, while Darwin inspires the representation of technology diffusion as an adaptive process that guarantees the survival of the fittest. Hence, firms that have adopted successful innovations gain comparative advantages over others, and therefore change the competitive environment. Firms that do not adapt - by adopting similar innovations or devising more efficient ones - are condemned to disappear.

While appealing, the implementation of these evolutionary models comes at a high theoretical price. Indeed, modeling the dynamics of rules and actions requires an abstract framework where, for example, products are defined as binary sequences of ones and zeros. Given highly complex dynamics, the models are mathematically intractable, and often their dynamics are far from intuitive. Hence, as suggested by Arrow (1995), the evolutionary approach is now considered as a point of view rather than a theory. Given these considerations, I believe that we still have to make important progress before being able to apply these types of models to empirical studies or policy analysis.

2.4 The Social Interactions Approach

There is a fourth, relatively new approach, to which I will refer as the Social Interactions (SI) approach. The approach is inspired by works on graph theory, statistical mechanics, and evolutionary game theory, and integrates many of the ideas of the epidemic, equilibrium, and evolutionary approaches. I classify in this category the works of Young (1998 and 1999), Durlauf (1997), Aoki (1995), Blume (1997), Ioannides (1997), Kirman (1997), and Robalino and Lempert (1999). Yet, the roots of the approach extend to at least Follmer (1974). Work by Arthur and Lane (1993) can also be considered to be related, or at least to have influenced this approach.

The SI approach is also based on multi-agent models. However, it differs from the evolutionary approach in that the models have more mathematical structure. This implies that there is an expanding "library" of mathematical theorems that helps researchers to analyze model dynamics or to interpret simulation results. Another nice feature is that the mathematical functions used to represent individuals' choices have functional forms that closely match those of multinomial choice models in econometrics, and therefore are well suited to empirical estimation (see Section 4). When applied to the analysis of technology diffusion, the SI framework highlights three main factors: a) agents' heterogeneity; b) imperfect information and bounded rationality; and c) social interactions.

Agents' heterogeneity is a necessary condition to replicate empirical data, in particular observed market shares and diffusion rates. Agents can differ on many dimensions. In the case of technology diffusion models, at least four should be considered: preferences, ownership of capital (i.e., size), geographic location, and economic sector. This four-dimensional heterogeneity is reflected in heterogeneous expectations about costs and benefits, for the same set of available information, and the same expectations generation process. However, the information set as well as the expectations generation process may also differ across agents, thus incorporating two additional dimensions of heterogeneity.

The idea that economic agents face imperfect information and are only boundedly rational is essential within the SI approach. Uncertainty is pervasive in the process of technology diffusion. Economic agents face uncertainty not only from imperfect information regarding the distribution of technology characteristics, but also from the dynamics of the economic environment. Yet, as opposed to the equilibrium approach, agents do not know intrinsically the true probability distribution of the random vectors characterizing technologies and the environment. Agents act rather as econometricians (see Sargent, 1992) and attempt to learn these probability distributions on the basis of available information. Convergence to a rational expectations equilibrium is a possibility, but not a precondition (see Grandmont, 1998a).

The introduction of social interactions in the technology diffusion process is probably the most novel contribution of this approach. Social interactions are considered important for two reasons. First, because in these interactions agents share information. This information then feeds the process through which agents generate expectations about new technologies and the economic environment. Hence, the type of existing social networks determines the quality and density of information flows. The second reason is that interactions are also sources of technological complementarities. For example, the cost for an Indian in the "paramo" region of the Andes to use a tractor to replace its cattle to farm may be prohibitively expensive. Indeed, fuel, replacement parts, and technical assistance can only be found several miles away from the peasant's village, in the closest middle size town. However, operation costs can be reduced if other neighbors adopt the new technology as well. First, there will be knowledge spillover regarding the maintenance and use of the tractors. But more importantly, a pull of adopters large enough may justify the location of a tractor maintenance garage that would also provide fuel and replacement parts, and brings maintenance costs down. Each new peasant adopting the technology will then generate a positive social externality, because he/she will help to bring costs down. Also, there can be negative externalities among users of existing technologies. As users shift to new technologies, the flow of knowledge regarding improvements in, or problems with the old technology will decline, as might the maintenance and supply base. Whether peasants within the village are able to coordinate the socially optimal solution depends mostly on the type of social interactions that they undertake. With no interactions, or if the interactions do not built trust and cooperative behavior, a socially efficient solution will not necessarily emerge. Therefore, the density of social networks, the strength of the connections between nodes, and the type of behavior associated with these connections will influence the diffusion of new technologies, and through this channel economic performance.

The theory of technology diffusion here finds its link with the theory of social capital formation. Observed levels of social capital will influence technology choices, policy choices, and ultimately economic growth. In the next section, I discuss the concept of social capital and how it relates to the concept of technology diffusion.

3. Social Capital and the Economy

3.1 Defining Social Capital

The concept of social capital is relatively new in economics. Broadly speaking, social capital refers to the set of social networks, norms, and formal and informal institutions that exist within a given economy and that shape individuals' interactions. By shaping these interactions, social capital influences individuals' behaviors and choices, and ultimately the evolution of the economic system. While many social scientists, in particular sociologists and anthropologists, have studied phenomena that in one way or another relate to social capital, its conceptualization is usually associated with the works of Putnam (1993) and Coleman (1988).

Putnam focuses on the structural dimension of social capital and defines it as the "horizontal associations" between people. More specifically, social capital consists of social networks and associated norms that have an effect on the productivity of the community. The key feature is that these associations tend to facilitate coordination and cooperation that benefit the members of the association. While Putnam only emphasizes the positive externalities of social networks, it is important to recognize that these externalities may also be negative. An often cited example is the Mafia in Italy, or terrorist networks (see Ronfeldt et al., 1998). In any case, for the "members" of the network, participation usually increases their welfare.

Coleman adds vertical associations to Putnam's horizontal associations. In Coleman's framework, social capital is the set of organizations that share two types of features: a) they incorporate some type of social structure; and b) they exist to facilitate coordination among actors. Firms, professional associations, or groups of associations with common goals fit this definition. Coleman's concept can be related in some aspects to the concept of Commercial Power Centers developed in Treverton and Leveaux (1998). As in Treverton and Leveaux's work, Coleman's associations do not need to be complementary or socially efficient. Indeed, most of the time, interests, goals and strategies are conflicting. This implies that higher levels of social capital (e.g.,

more diversity and cohesion within associations) do not necessarily lead to higher levels of social welfare. Rather, the theory suggests the existence of a non-linear relationship between the level of social capital and welfare. Very high levels or very low levels of social capital are both undesirable outcomes.

Putnams and Coleman's definitions concentrate on what I call informal associations. However, social capital in large also incorporates a formal dimension. This dimension can be assimilated with Engels and Marx's concept of super-structure, made of political and legal institutions that define the space of actions and strategies of individual and informal organizations. North (1990) develops an economic theory for these institutions, explaining how they emerge and evolve (North also analyzes informal institutions). According to North:

"Institutions include any form of constraints that human beings devise to shape human interactions [...] Institutions affect the performance of an economy by their effect on the costs of exchange and production. Together with the technology employed they determine the transaction and transformation costs [of the economy]."

In this framework, institutions can be thought of as the rules of the game, while organizations and networks can be thought of as the implementation of specific strategies in the game.

3.2 Measuring Social Capital

I believe there is wide consensus that social capital is an important concept to explain the process of economic development (see my discussion in Sub-sections 3.3, 3.4, and 3.5). The main complication, however, is that behind its intuitive appeal, rises the problem of measurement. As stated by Abramovitz (1986) "no one knows just what it means [social capital] or how to measure it". Nonetheless, I claim that in the past years, economists and sociologists have made considerable progress not only on measuring the level of social capital, but also on quantifying some of its effects.

The World Bank recently created a discussion list on social capital (see World Bank, 1999a). One of its objectives is to improve the characterization and the measurement of social capital. The approach has been to clarify the dimensions of social capital (e.g., participation in groups or generalized trust) in order to develop tools to measure social capital in different contexts (see Narayan, 1997). There are two approaches that have been emphasized: a) the measurement of typologies, structures or interconnectivity of groups and social networks; and b) the measurement of norms. These two types of measurements are intimately related. Indeed, within each structural unit, social relations are guided by norms, rules, beliefs, mores and habits that create expectations. Under particular conditions, norms can evolve to become generalized beyond the specific social relationship where they emerged (see Narayan, 1999).

Not surprisingly, the main instruments for the measurement of social capital, at least at the micro level, are surveys of households and firms. For example, in order to estimate the density of social connections, household heads are asked about membership in different groups and frequency of interaction. Then, it is possible to compute indexes of social capital, that include density and characteristics about informal groups, formal groups, and networks to which people belong (see Narayan and Prichett, 1996, for an application to Tanzania). Studies have also been developed at the community/local level (see for example the Local Level Institutional Study, LLI implemented in Bolivia, Indonesia, and Burkina Faso, World Bank, 1999b). In addition to the structural measures, this survey collects institutional information, in particular related to services provision and quality. Regarding the study of norms and values, one is referred to the World Values Survey by Ingleharts (1997). The questions used in the survey are of the form: "Would you say that most people can be trusted or that you can [be trusted]?". An interesting study by Knack and Keefer (1995) uses the results of this survey to show a positive relationship between trust and the levels of investment in a given country. At the more aggregate level, the international survey of business leaders conducted by Porter and Christensen (1999b) can also be viewed as an attempt to measure proxies for social capital.

At the macro level, researchers have had a tendency to rely on proxies for social capital computed by less rigorous and reliable methods. These indicators have been developed originally to measure the strength of institutions within countries, civil rights, democracy, as well as social stability and social cohesion. Some of these indicators (e.g., the Ethno-Linguistic Fractionalization Index) were used in the last chapter in my econometric analysis of the determinants of depletion rates. As I discuss in the next section, these indicators have also been used extensively to explain differences in growth rates among countries (see Fedderke and Klitgaard, 1998 for an interesting review). Results based on these indicators, however, need to be taken with circumspection. Indeed, authors' subjectivity is pervasive in their construction. Some of them can be regarded as proxies for what Fukuyama (1993) calls "spontaneous sociability", or the ease with which strangers interact with one another; and the "radius of trust", which is the size of the group with which a person will extend relations of trust. These values, according to Fukuyama, underlie societies' ability to form increasingly complex organizations, and therefore act to form social capital.

3.3 Social Capital and Economic Performance at the Macro Level

There is a rich literature on the role of institutions and more informal forms of social capital in economic growth. Usual references include the works of Barro (1997), Alesina and Rodrik (1994), Sachs and Warner (1995), Collier and Gunning (1999), Knack and Keefer (1995), Mauro (1995), and Temple and Johnson (1998). New references include Fedderke (1997) and Fedderke et al. (1999). The conclusions seem to be unanimous: institutions matter, and so do social interactions and social stability.

For example, Temple and Johnson (1998) analyze growth rates in Sub-Saharan Africa. The authors extend the work of Adelman and Morris (1968) and use ethnic diversity, social mobility, and the prevalence of telephone services as proxies for the density of social networks. They show that these factors can explain significant amounts of variations in national economic growth rates. More recently, Collier and Gunning (1999) discuss the role of social capital

as an explanatory factor for the observed differences in GDP per capita growth rates between Africa and other regions of the world. The authors write:

"Social capital can be generated both by the community and by the government. Civic social capital is the economic benefits that accrue from social interaction. These economic benefits can arise from the building of trust, from the knowledge externalities of social networks, and from an enhanced capacity for collective actions. Public social capital consists of the institutions of government that facilitate private activity, such as the courts [...] On various measures Africa is relatively lacking in both types of social capital [...] Possible barriers to social interactions are Ethno-Linguistic fractionalization and inequality."

The authors show that Africa has a strikingly high level of fractionalization. For example, the Ethno-Linguistic Fractionalization index (ELF) - constructed as the probability that two randomly drawn citizens are from different ethno-linguistic groups - is twice as high in Africa than in other developing regions. This is a critical result, since it has been found that a one point increase in the Ethno-Linguistic Fractionalization index reduces the growth rate of GDP per capita by -0.016 percentage points (see Easterly and Levine, 1997).

One needs to be careful, however, with the interpretation of the results. In the case of the ELF index, a possible interpretation would be that more homogenous societies tend to work better than non-homogenous ones. This is clearly in contradiction with new results that suggest that diversity reduces complexity, and therefore acts in favor of higher economic efficiency (see Page, 1999). Then, an important possibility to consider is that the effects of these indicators on economic growth are truly non-linear. Hence, high heterogeneity and high homogeneity are both undesirable outcomes. My econometric results in Chapter 2 provide support for this idea.

Another study using proxies for networks' density was conducted by Kedzie (1997). Kedzie used a quasi-global panel of developed and developing countries to show the importance of social networks for democracy. Although he does not talk explicitly about social capital, his measure of interconnectivity can be considered as a proxy for the structural dimension of

social capital. Given the well-known result that democracy is correlated with economic growth (see Barro, 1997), his result can also be interpreted as showing an indirect linkage between social capital and economic growth.

3.4 Social Capital and Economic Performance at the Micro Level

At the micro level, social capital plays an important role as well. There are usually two functions that are in one way or another considered in the literature. The first is that social capital *improves information flows*. The second is that social capital *facilitates coordination and cooperation*. I briefly discuss each of these in turn[1].

Individuals are often forced to evaluate actions for which the outcomes are uncertain. Uncertainty can be thought to exist at three levels: a) uncertainty about the exogenous factors that affect our decisions (e.g., prices, weather, and performance of new technologies); b) uncertainty about the behavior of other agents; and c) uncertainty about the process that links our actions, actions of others, and the environment to final outcomes. Social capital is supposed to improve information flows, and therefore reduce uncertainty. We can think of the reduction in uncertainty as the reduction in the variance of individuals' expectations that results from an update process that takes place in the presence of new information flows. Hence, associations of producers of corn in Los Andes may be able to generate more robust expectations about the price of corn, the path of government policies, or the characteristics of new fertilizers than individual farmers. Associations may also improve the knowledge that each member has about the possible behavior of others. In a recent study, the World Bank analyzes the effect of social capital on *information failures* (see Dixon et al., 1998, Chapter 6):

"Decisions by economic agents are often inefficient because they lack adequate or accurate information. In some circumstances, agents have incentives to provide incorrect information to other agents. Social capital may improve these situations. Although it does not remove the uncertainty it can increase mutual knowledge about how agents may respond to different

states. It may also serve as an enforcement mechanism to ensure that these expectations about mutual behavior are in fact realized. This reduces contracting costs."

It is important to notice that more and better information does not necessarily imply better coordination. However, social networks can also contribute to better coordination. There are two situations in which coordination failures may occur, meaning that a joint action that would have maximized social welfare is not undertaken.

A first situation is one in which the action is not implemented by all, although all the agents have "coordinated" the optimal action. This occurs when the action is not enforceable, and some agents have incentives to deviate from the social agreement. This usually implies that the expected benefit of deviating is higher than the expected costs. By promoting repeated interactions and generating knowledge about each member's preferences and personality, social capital may reduce the likelihood of this type of outcome, for example by identifying and excluding from the social contract the individuals that the community considers will not be able to comply. Hence, social capital would reduce risk for all of the remaining actors. In this case, the social action does not need to be risk-efficient in the sense of game theory. In other words, although incentives to deviate may still exist, individuals will simply elect not to do so. Formally, this type of behavior can be generated by saying that individuals incorporate a social component with a non-zero coefficient in their utilities. This is different from the case where a set of firms agree to collude because the collusion is globally efficient but also risk dominant.

The second source of failure is usually associated with the prisoner's dilemma. Here, for some exogenous reason such as high transaction costs, there is no ex-ante coordination. In this case, uncertainty about the behavior or actions of other individuals entails that the risk efficient choice differs from the socially efficient choice (see my discussion in Section 4). For example, the adoption of a new technology may be highly beneficial to a given farmer and its neighbor, if they both adopt the technology. However, if one does not adopt, the costs for the farmer that adopts the technology may be prohibitively high. If the expected losses for an adopter are higher than the

expected losses for a non-adopter, neither of them will adopt. Social networks may enhance coordination by improving communication. This does not imply, however, that the socially optimal action will be undertaken. As mentioned earlier, even if a coordinated strategy exists, agents may have incentives to deviate. The same study from the World Bank (see Dixon et al., 1998, Chapter 6) states:

"Uncoordinated or opportunistic behavior by economic agents can also lead to market failure. This can occur as a result of imperfect information but also simply because the benefits of not complying with an agreement or an expected line of behavior (a "norm") are greater than the expected penalty [...] Associations reduce opportunistic behavior by creating repeated interaction among individuals, which enhances trust [...] A cohesive association creates trust and substitutes the individual utility function by a collective utility function and it is the latter that is maximized. This can occur in vertical or horizontal associations but is more likely in horizontal ones such as those based on kinship or other dense networks based on gender, ethnicity or caste. The stability of the networks is an important requirement for its efficiency. Hence, a development path characterized by massive urban-to-rural migration will tend to erode social capital."

There is an expanding empirical literature on the links between social capital and economic performance at the micro level. I classify this literature into two groups: those studies that emphasize the role of social networks and associations, and those that emphasize the role of preferences and behaviors. In the first group, Narayan and Pritchett (1996) show that in Tanzania, a one standard deviation increase in village-level social capital increases household income per person by 20% to 30%. By comparison, a one standard deviation increase in schooling - nearly three years of additional education per person - increases income by only 4.8%. In this study, social capital indexes were constructed on the basis of data gathered through institutional mapping, using Venn diagrams to discuss associational life in eighty-seven villages. The number and types of groups, trends in membership, and reasons for joining were considered. Trends of generalized trust among institutions and village members, and levels of village-level unity were explored through interviews. A potential problem with the robustness of these results, however, is that the measure of social capital is itself an endogenous variable. Hence, high income households may be more likely to choose to

belong to alternative networks, or face higher social demand to be part of these networks. From the original study, it is not clear how the authors controlled for this endogeneity problem.

There is also evidence that social networks have played an important role in promoting sustainability in rural communities in the Andean regions of Ecuador and Bolivia (see Bebbington, 1997; and Bebbington et al., 1997). The authors present some descriptive statistics and qualitative data that suggest that more integrated communities have taken advantage of environmental niches, production of high-value marketed products, and incorporation of modern technologies into the production process. The argument is that social networks play important roles in fostering sustainable resources management and livelihood development. The authors stress, however, that economic incentives are also a necessary condition.

The informational benefits of social capital have also been explored in the context of social networks of leaders of rural communities in Missouri (see O'Brien et al., 1998). The authors use logistic regressions to show that leaders in more "viable" communities were more likely to have worked with one another on community projects than leaders in the less viable communities. Unfortunately in this study it is not clear whether cooperation is the result of the degree of "viability" (i.e., leaders from "viable" communities have incentives to cooperate). Another study, Morten (1993), shows that networks of private and public business activities in several Norwegian communities (Actions Research Projects, AR), have facilitated the development process to discover meaningful economic development activities. This occurs as "community members identify, discuss and prioritize local economic development projects".

Studies in the second group analyze social capital in terms of altruistic or cooperative behavior. For example, Hyden (1993) looks at the determinants of social capital in Tanzania, as proxied by an individual's willingness to act in the interest of his/her community, as opposed to his/her own interest. Hyden provides econometric evidence that four factors are associated with individuals' "willingness to invest" in this type of social capital: economic growth, social stratification, economic decline (for the individual), and

cultural homogeneity. Hyden concludes that, in many cases policies designed to "get the prices right" have eroded social capital by reducing economic growth and increasing social stratification. Another study in this vein of research (see Lindon and Schmid, 1998) associates social capital with attributes such as caring, goodwill, loyalty, sense of belonging, sense of community, or social closeness. The authors argue that increases in social capital in rural communities will be more important than investments in education to increase productivity and economic performance.

3.5 Social Capital and Technology Diffusion: the Case of Hybrid Cocoa in Ghana

A highly original study recently published in the Journal of Policy Modeling provides evidence of the effects of social networks on the adoption of agricultural innovations in developing countries (see Boahene et al., 1999). The authors study the adoption of hybrid cocoa in Ghana. Given the importance of the study for my research, I review its main contributions in detail.

The authors state that many of the technological innovations in Ghana have taken place in the agricultural sector. In the case of cocoa, one of these innovations is hybrid cocoa (also called series 2), which appears to have higher productivity than other varieties of cocoa (e.g., Amazons and Amelonado). In particular, it allows more than two harvests per season. Surprisingly, only 10% of farmers have adopted this variety. This is in part explained by higher direct and indirect costs associated with information, labor, land, chemicals, inputs, and machinery. As I mentioned in Section 2, different responses to the adoption of a new innovation reflect the existence of heterogeneous producers who derive different costs and benefits from it. In Ghana, farmers differ in their social position, and therefore in their level of access to resources from friends, family, or the financial system. Each farmer also evaluates risk differently. In the case of hybrid cocoa, this risk is associated with a level of yield that is higher, but uncertain.

To formalize the process of adoption of hybrid cocoa, the authors developed a heuristic model that I have reproduced in Figure 3.1. The fundamental

assumption is that farmers adopt hybrid cocoa to maximize their utility, and that this utility depends on expected profits, but also on expected social rewards. These rewards "include the recognition and approval that society accords the farmer for being a successful innovator and for meeting social obligations". The amount of social obligations is defined as "the number of relatives who depend on the farmer for their livelihood". The authors consider that farmers face two types of uncertainties: objective uncertainty that is related to the yield variability in response to changes in weather; and subjective uncertainty that is related to their initial limited knowledge regarding how hybrid cocoa operates (e.g., types of chemicals, new farming practices, planting procedures, pruning, and spraying).

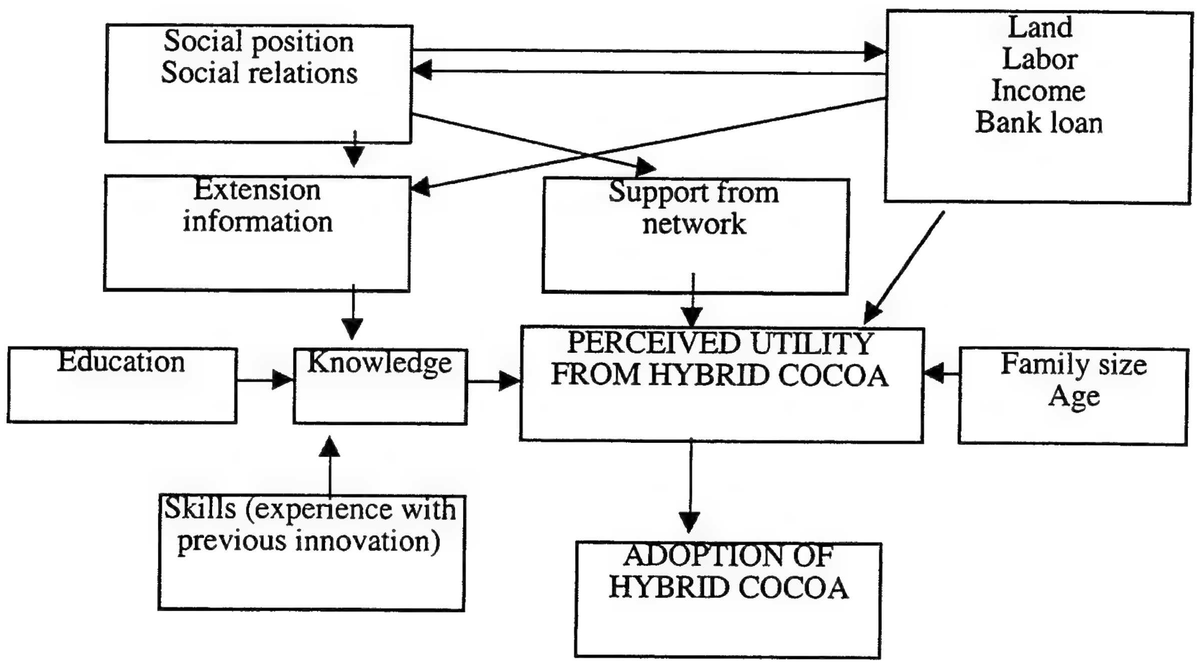

Figure 3.1: A Model of Adoption Behavior.

Source: Boahene et al. (1999).

Adoption costs are related to the opportunity cost of cash in advance that is required to purchase the inputs necessary to cultivate hybrid cocoa; the land needed for new planting; the labor for land preparation, planting of seeds, spraying, pruning, and harvesting of crops; the fixed costs associated with money and time spent in searching for information from cocoa institutions; and the time spent in making contacts and arrangements with traders and suppliers

of inputs. The existence of these fixed costs suggests that hybrid cocoa should be more profitable for big farmers than small farmers.

In their model, the authors also assume that access to improved information has a positive effect on the adoption of hybrid crops, because it creates awareness about innovations and new production procedures. There are two sources of information: extension agents that represent cocoa institutions, and social networks. The authors write:

"[...] extension information involves costs, both in terms of time and money spent in visiting the extension agents. The highly educated or skilled farmers will incur lower information costs because they are able to evaluate and understand information much more easily, and hence visit the extension agents less frequently. Farmers who lack the means to acquire information from the extension agents or who are uneducated can rely on the information from their social networks. Farmers often socialize at the market place, during communal gatherings, and at other similar occasions. Embedded in their discussions is often information related to farming [...] Because acquaintances who have not been successful with hybrid cocoa tend to confer negative signals, it is supposed that only farmers who are in a network of relations with many previous successful adopters have access to a large network information and, therefore, will be more likely to adopt the hybrid cocoa."

Social networks have a second crucial role in their model. That is, farmers obtain support such as labor or machinery from their networks: labor obtained by cocoa farmers from their acquaintances is called in Ghana "noboa" or "cooperative labor". In this type of system, farmers take turns in helping each other on their farms without involving payments of wages. As the authors argue, this type of labor is cheaper because:

"The team spirit embodied in the cooperative system encourages members to work harder than they would if they were working on their own [...] Farmers with access to cooperative labor are likely to incur a lower labor cost, and thus, perceive the innovation to be more profitable. Other sources of support gained via social networks, namely machinery, remittance, and occasional help obtained for spraying cocoa or harvesting crop may all contribute toward a reduction in production costs."

To evaluate the linkages between the different components of their model, the authors used a random sample of 103 farmers in the Suhum and Nkawkaw

districts. For these farmers, cocoa is an important activity (they either have an output of more than 60Kg/year, or a cocoa farm of more than 0.4 hectares). Fifty of the farmers were adopters, while fifty-three were non-adopters. The adopters adopted hybrid cocoa for the first time after November 1989. The survey enabled the researchers to gather information about the farmers' socioeconomic status and their social network. Using this data, the authors estimated logistic regressions of the probability of adoption. I have reproduced one of these regressions in Table 3.1.

Variables (n=103)	Model 1
Frequency of Contact of Extension Agents (1-7)	0.50** (0.26)
Income (kgs)	0.0011 (0.0012)
Bank loan (0-1)	1.51** (0.67)
Family size (no. of people)	-0.12 (0.15)
Age (years)	-0.05** (0.02)
Education (years)	.0111* (0.075)
Hired labor (persons per hectare)	0.041* (0.025)
Skill (0,1)	0.21 (0.73)
Land (hectares)	-0.08 (0.19)
Cooperative labor(0-1.3)	2.72*** (1.00)
Previous adopters (no. of people)	0.81*** (0.31)
Network support (0-9.3)	0.06 (0.17)
Family labor (persons per hectare)	0.020 (0.026)
Social Status (0,1,2)	-0.68 (0.57)
(Status)_	0.76 (0.74)
Intercept	-5.41 (2.32)
-2 Log Likelihood	93.06
McFaden R_	0.35

* Represents significance at 10%, ** at 5%, and *** at 1% respectively; tested at one-tail probability. Standard errors are in parentheses. Variables are indicated with their units or range.

Table 3.1: Determinants of the Probability of Adoption of Hybrid Cocoa in Ghana.

Source: Boahene et al. (1999).

The results strongly confirm their hypothesis of the importance of social networks. These results and their policy implications are best summarized by the authors. They write:

"The empirical evidence shows that in the adoption of hybrid cocoa, the support that small-scale farmers obtained via their social networks is more relevant than the advantage of farm size enjoyed by large-scale farmers [...] The study has shown that the adoption of hybrid cocoa is a process of incorporating different mechanisms and factors - both economic and sociological. Factors, such as bank loans and hired labor, have significant positive impact on adoption. Also, education and the amount of information accumulated from extension agents are important in determining whether or not a farmer becomes an adopter. However, access to land, income, and skills have no significant effect on adoption. The generally low income

from farm and off-farm activities may explain the low impact of farmers' income on adoption [...]

According to economic theory, the chance of farmers adopting hybrid cocoa should increase with farm size since adoption involves fixed costs. The sources of fixed costs include cost (monetary and time) incurred in acquiring information from extension agents and the cost of a mechanical spraying machine. In this study, the inclusion of a social support in the adoption model has shown that these economic constraints can be overcome to facilitate adoption by farmers, irrespective of their scale of operations. Thus, an integrated approach helps avoid the limitations often associated with mono-disciplinary models in innovation adoption [...]"

3.6 Social Capital within this Research

As I have shown, social capital is still a relatively nebulous concept composed of multiple dimensions and complex channels of interactions within the economy. Yet, there is growing evidence, with different levels of robustness, that by affecting information flows and promoting cooperative behavior, social capital promotes the adoption of socially efficient technologies and enhances or discourages economic growth.

My interest in this research is to formalize two ideas/insights that are associated with the structural dimension of social capital, and that I consider important determinants of the process of technology diffusion. The first idea is that social networks affect the ways in which agents interact and exchange information. Therefore, social networks within the economy affect information flows which have two fundamental roles. First, this information is used by economic agents to update their expectations about different factors that determine the costs and benefits of alternative technologies. Second, but not less important, this information affects the process of learning-by-using current technologies. For example, the type of social networks will define how fast information about better production practices of a given technology diffuses across the population of users. By affecting the learning-by-doing process, social networks affect productivity growth, and indirectly affect operation costs. For example, the absence of

these knowledge externalities in Africa is one of the factors emphasized by Collier and Gunning (1999) to explain poor economic performance.

The second idea is related to coordination failures. I have discussed that in many settings, the operation costs of a particular technology or its productivity depend on its number of users. Hence, socially optimal adoption decisions may often require coordinated actions. Some types of networks may be more prone to coordination than others. This implies that diffusion dynamics, growth paths, and policy choices will be sensitive to the prevalence of cooperative behavior.

The remainder of this chapter explores concepts and mathematical tools that can be used to formalize these two ideas within a model of technology diffusion. More precisely, the goal will be to model the set of formal and informal business networks that exist within an economy, and the process through which the network shapes firms' strategies, and in particular technology adoption decisions. The types of networks that I consider can be grouped into *classes* according to three features: a) the *density* of connections; b) the intensity of these connections; and c) the type of behavior associated with them. The *density* of networks will fundamentally affect the quantity and quality of information flows. The *intensity* of network connections will determine the levels of social spillovers. Finally, we saw that the existence of a network does not imply that its members will coordinate actions optimally; coordination will depend for example on levels of trust, and the frequency of interactions. To capture these effects, each class of networks that I study is also associated with the probability of observing one of two types of behaviors: cooperative behavior or non-cooperative behavior. In summary, different types of networks will generate: a) different levels of knowledge spillovers; and b) different levels of cooperative behavior.

Each *class* of networks supports multiple network typologies. This is, more than one set of connections is consistent with a given average number of connections per capita. The rationale for working with classes of networks instead of specific typologies, is that at the macro level the latter are very rarely, if ever, observed. However, we observe proxies for levels of

connectivity (see Collier and Gunning, 1999; and Fukuyama, 1993) that help to establish a link between models and reality.

4. Modeling Social Capital and Social Interactions

In Section 2, I described briefly some features of what I called the Social Interactions approach. Here, I explore in more detail some of the models that have been constructed within this tradition. I describe how these can be used to formalize the concept of social capital and provide a better representation of the technology diffusion process.

The analysis of economies with interacting agents using tools from statistical mechanics goes back to at least Follmer (1974). There seems to have been a rupture, so that the literature on the issue was relatively scarce during the '80s. Hence, the concepts that I discuss in this section are relatively new to economics. This being the case, the reader will find in Appendix 8.4 a set of definitions for some of the concepts used here.

I shall discuss briefly three models that provide some interesting insights to Social Interactions models. The first model is due to Young (1999) and uses potential games and Gibbs states to derive stable stochastics states for a given multi-agent system. In my application, these states can be thought of as technology choices. Young's model is important because it shows how we can model cooperation in technology choices. Also, the model illustrates how in the absence of cooperation, stable states are not necessarily socially efficient.

The second and third models are due to Follmer (1974) and Durlauf (1993) and discuss the convergence properties of technology choices within a multi-agent model. These models are important because they show how convergence to an optimal equilibria depends on the level of spillover effects resulting from the intensity of network connections.

These three models inspire the development of the agent-based model of technology diffusion developed in Chapter 5.

4.1 Potential Games, Gibbs States and Social Efficiency

Young's model is a game played on a graph Γ (i.e., a social network) with a finite set V of vertices and a set E of unidirected edges. Each vertex represents an agent, and the set of neighbors for each agent is given by v(i). Agents choose between strategies A and B according to the following pay-off matrix:

	A	B
A	a	c
B	d	b

(3.4)

where a>d and b>c. Each choice can be associated with a given technology, while the pay-off implicitly determines the level of spillover effects. Notice that a dominant choice (A,A) or (B,B) may require coordination.

The state of the system is a set $\mathbf{x}$ made of choices x_i by agents i. The utility of any agent in a given state $\mathbf{x}$ is:

$$U_i(\mathbf{x}) = \sum_{j \in \upsilon(i)} w_{ij} u(x_i, x_j) + v(x_i), \tag{3.5}$$

where w_{ij} is the weight (importance) that agent i places on connection j, u(.) is the utility function based on matrix (3.4) that gives the pay-off of the choice of agent i as a function of the choice of its neighbors, and v(.) is a function that gives intrinsic utility from choice x_i (i.e., utility that is independent of the choices of other agents).

Agents are assumed to play this game at random times with their neighbors. Young further assumes that agents are likely to deviate from the best reply dynamics with some probability. Hence, agent i's choice is given by a log-linear response model:

$$\Pr\left\{i \ \ chooses \ \ A \ \ in \ \ state \ \ x\right\} = \frac{e^{\beta U_i(A|\mathbf{x}_{-i})}}{e^{\beta U_i(A|\mathbf{x}_{-i})} + e^{\beta U_i(B|\mathbf{x}_{-i})}}, \qquad (3.6)$$

where β is a parameter that captures the degree to which the agent will deviate from the optimal solution. The higher the β, the lower the probability that the agent will deviate.

The individual choice model (3.6) can be associated with a global probability measure (i.e., a function that gives the probability of observing a particular state **x**) that turns out to be a Gibbs state (see Appendix 8.4). This probability measure is given by:

$$\mu(x) = \frac{e^{\beta\rho(x)}}{\sum_{y\in\Xi} e^{\beta\rho(y)}}, \qquad (3.7)$$

where Ξ is the set of all possible configurations of choices and

$$\rho(\mathbf{x}) = (a-d)A(\mathbf{x}) + (b-c)B(\mathbf{x}) + V(\mathbf{x}) \ , \qquad (3.8)$$

is the potential function of the game (i.e., the potential associated with a Gibbs state). This potential function can be thought of as giving the total amount of utility within the system. Hence, A(**x**) is the sum of weights of all edges {i,j} such that $x_i = x_j = A$, B(**x**) is the sum of weights of all edges {i,j} with $x_i = x_j = B$, and v(**x**) = $\sum_{j\in\nu(i)} V_i(x_i)$.

There are two interesting features in this model. The first is that because the potential function is a Gibbs state, the most likely state **x** is the one that maximizes the potential function. Young calls this state the *stochastically stable state.* Moreover, as β increases, the probability that the state will be in a state that maximizes the potential also increases. This result is intuitively consistent with 3.6. If β is not "too small" each agent will be more likely to choose the risk dominant strategy. In the aggregate, this individually risk dominant strategy will become the stochastically stable strategy. We can interpret this result by saying that even if individuals

make mistakes in their decisions, the system will spend most of the time in states that maximizes individuals' utility, as long as the mistakes are not pervasive (i.e., β is not extremely low). The other interesting feature of the model is that the optimal stochastically stable state is *not* necessarily a social optimum. To see this, consider the case where V(x)=0 (i.e., agents do not derive intrinsic utility) and a-d > b-c and a<b. In this case, a configuration **x=A** (i.e., all agents choose A) is stochastically stable, but because b>a, the socially efficient configuration is **x=B.**

4.2 Multiple Equilibria and Network Connections' Intensities

The model that I consider in this section is based on Follmer (1974). The author treats the particular case where the graph (i.e., the social network or set of social networks) is a lattice and the set of neighbors for any agent i are given by $\upsilon(i)=\{j;|i-j|=1\}$. Furthermore, the set of technology choices is restricted to S={1,-1}. Under the assumption that choices at time t are only a function of choices at time t-1, the probability distribution of configurations **x** at time t is given by:

$$\Pr(\mathbf{x}_t) \sim \exp\left(\beta h \sum_i \sum_{j\in\nu(i)} x_{it} x_{jt-1}\right), \qquad (3.14)$$

In this case, the importance of agents interactions is captured by the parameter h. Notice that each time that the choice of a neighbor j is different from the choice of an agent i, the product $x_{it}x_{jt-1}$ is negative. Follmer showed that there exists an h_c such that if h<h_c, the mean choice will converge to zero. This implies that each technology will hold 50% of the market. On the other hand, if h>h_c, the mean choice will converge to one of *two* non-zero values. Basically, one of the technologies will dominate the market. The probability of converging to any of these values depends on the initial set of choices $\mathbf{x}_0$. Hence, if the intensity of connections is "high", which technology dominates the market is a matter of chance. On the other hand, for low connections' intensities, dominance is never observed.

4.3 Non Ergodic Growth

The final model that I present is related to Durlauf (1993). This model will help us understand the dynamics of the simulation model that I develop in Chapter 5. Durlauf's theoretical development attempts to explain empirical evidence about differences in growth rates among countries (see Delong, 1988; Quah, 1992 and 1996; and Durlauf and Johnson, 1992). One way to account for long run differences is to say that we observe different steady states because economies are structurally different (see Barro, 1997), but that each economy has a single steady state. However, if differences remain after controlling for microeconomic heterogeneity (assuming that the controls are sufficient), another theory is necessary. One possibility is to introduce increasing returns to scale in the standard neo-classical model (resulting from human capital accumulation by individual agents will increase the productivity of other agents through the economy), thus leading to the existence of multiple steady states (see Romer, 1986; Lucas, 1988; and Azariadis and Dranzen, 1990). The limitation of this model is that it does not mention how any of the steady states are selected. Durlauf takes a different approach and is able to explain the existence of multiple steady states even for identical initial conditions. He uses random field methods to analyze the evolution of a countable set of industries over time. He demonstrates that technological complementarities create intertemporal linkages between the production functions of each economic sector, in ways similar to social increasing returns models. When these complementarities are strong enough, coordination failures may occur that affect long-run behavior. Durlauf assumes that there is a set of industries within the economy that act competitively. Each industry chooses a capital stock sequence K_{it} to maximize expected discounted profits given by:

$$\Pi_{it} = E\left(\sum_{j=0}^{\infty} \beta^{t+j}\left(Y_{i,t+j} - K_{i,t+j}\right)\middle|\mathcal{F}_t\right), \qquad (3.15)$$

where Y is output and $\mathcal{F}$ represents the available information at time t. There are two production technologies that are given by:

$$
\begin{aligned}
Y_{1,t+1} &= f_1\left(K_{i,t} - F, \mathcal{F}_{t\text{-}1}\right) \\
Y_{2,t+1} &= f_2\left(K_{i,t}, \mathcal{F}_{t\text{-}1}\right)
\end{aligned}
\quad , \qquad (3.16)
$$

where F is an overhead capital cost associated with technology 1. The dependence of the production functions on $\mathcal{F}$ reflects the presence of spillover effects from the history of production decisions to the productivity of the economy at time t. Durlauf defines complementarities locally. Hence, the productivity of each industry at time t is affected only by the production decisions of a finite number of industries at time t-1. The set of industries which affect industry i is given by:

$\Delta_{kl} = \{i-k,\ldots,i,\ldots,i+l\}$ with k,l>0. Then for each firm i, Durlauf defines ω_{it} that is equal to 1 if technique 1 is used, or 0 otherwise.

The following assumptions govern the interactions between industries' production functions:

$$
\begin{aligned}
f_1\left(K_{i,t} - F, \mathcal{F}_{t\text{-}1}\right) &= f_1\left(K_{i,t} - F, \omega_{j,t-1} \forall j \in \Delta_{k,l}\right) \\
f_2\left(K_{i,t}, \mathcal{F}_{t\text{-}1}\right) &= f_2\left(K_{i,t}, \omega_{j,t-1} \forall j \in \Delta_{k,l}\right)
\end{aligned}
\quad , \qquad (3.17)
$$

Equation (3.17) states that the production functions depend on the technique choices at t-1. Furthermore, the relative productivity of f_1 (technique 1) at time t is enhanced by choices of technique 1 at time t-1. Hence, if ω' and ω'' are two realizations of the set of choices ($\mathbf{w}_{t-1}$) at time t-1 such that $\omega_j^{'} \geq \omega_j^{''} \forall j \in \Delta_{kl}$ (i.e., such that technology 1 is used instead of technology 2 for all industries in the set of spillovers), then:

$$
\begin{aligned}
&f_1\left(NK_{it}, \omega_{jt-1} = \omega_j^{'} \forall j \in \Delta_{kl}\right) - f_2\left(NK_{it}, \omega_{jt-1} = \omega_j^{'} \forall j \in \Delta_{kl}\right) \\
&\geq f_1\left(NK_{it}, \omega_{jt-1} = \omega_j^{''} \forall j \in \Delta_{kl}\right) - f_2\left(NK_{it}, \omega_{jt-1} = \omega_j^{''} \forall j \in \Delta_{kl}\right)
\end{aligned}
. \qquad (3.18)
$$

With these assumptions (and two additional assumptions regarding the shape of the production functions and the availability of the stock of capital), Durlauf derives the following theorem (the proof is simple and can be found in the Appendix of Durlauf, 1993):

Theorem 2.1 of Durlauf (1993): In equilibrium, the conditional probability measure for each industry's output, capital stock, and technique obeys:

$$\mu\left(Y_{i,t+1}, K_{i,t}, \omega_{i,t} \middle| \mathcal{F}_{t-1}\right) = \mu\left(Y_{i,t+1}, K_{i,t}, \omega_{i,t} \middle| \omega_{i,t-1} \forall j \in \Delta_{k,l}\right), \tag{3.19}$$

The theorem states that there exist transition probabilities that relate technology choices today to technology choices tomorrow. By implication, today's technology choices completely characterize today's information set. It is unnecessary to know the technology choices of prior periods.

In order to analyze multiple long-run equilibria, one additional restriction is added:

$$\mu\left(\omega_{it} = 1 \middle| \omega_{jt-1} = 1 \forall j \in \Delta_{kl}\right) = 1 , \tag{3.20}$$

This restriction states that if all neighboring industries adopt technology 1, then the probability that industry i will adopt technology 1 is equal to 1. Multiple equilibria exist if for some initial conditions, $\mathbf{w}_\infty = 1$ fails to emerge as time grows. If $\mathbf{w}_0 = 0$ favorable industry shocks will periodically induce industries to produce with technology 1. With strong spillovers, these effects may build up, allowing $\mathbf{w}_\infty = 1$. However, if the spillover effects are weak, multiple equilibria may emerge. In particular, if for analytical purposes we put boundaries on the probability that an industry will choose technology 1 even if some of the neighboring industries adopt technology 2, that is if:

$$\theta_{kl}^{\min} \le \mu\left(\omega_{it} = 1 \middle| \omega_{jt-1} = 0 \;\; for \;\; some \;\; j \in \Delta_{kl} \right) \le \theta_{kl}^{\max}, \tag{3.21}$$

then the following theorem holds:

Theorem 3.1 of Durlauf (1993): For each index set Δ_{kl}, with at least k or l non-zero there are numbers $\bar{\theta}_{kl}$ *and* $\underline{\theta}_{kl}, 0 < \underline{\theta}_{kl} < \bar{\theta}_{kl} < 1$ such that:

A. If $\theta_{kl}^{\min} \ge \bar{\theta}_{kl}$, then $\mu(\omega_{i\infty} = 1 | \mathbf{w}_{-1} = 0) = 1$

B. If $\underline{\theta}_{kl} \ge \theta_{kl}^{\max}$, then a) $\mu(\omega_{i\infty} = 1 | \mathbf{w}_{-1} = 0) < 1$ and b) $\mu(\mathbf{w}_{\infty} = 1 | \mathbf{w}_{-1} = 0) = 0$.

Part A of Theorem 3.1 states that if the probability that any industry will choose technology 1 given that some its neighbors choose technology 1 is high (i.e., spillover effects are high) then in the long run all industries will adopt technology 1 almost surely. On the other hand, part B of the theorem states that if the spillovers are low (i.e., the probability that any industry will choose technology 1 given that some of its neighbors choose technology 1 is low), then the probability that in the long run any industry chooses technology 1 is less than one, while the probability that all industries choose technology 1 is zero. In this latter case, several equilibria with varying degrees of productivity are possible. As an illustration, consider the case with interaction range equal to three: $\Delta_{11} = \{i-1, i, i+1\}$. The transition probabilities can then be written as:

$$\begin{aligned}
&\mu\left(\omega_{it} = 1 \middle| \sum_{j=-1}^{1} \omega_{i-jt-1} = 3 \right) = 1 \\
&\mu\left(\omega_{it} = 1 \middle| \sum_{j=-1}^{1} \omega_{i-jt-1} = 2 \right) = \theta_1 \\
&\mu\left(\omega_{it} = 1 \middle| \sum_{j=-1}^{1} \omega_{i-jt-1} = 1 \right) = \theta_2 \\
&\mu\left(\omega_{it} = 1 \middle| \sum_{j=-1}^{1} \omega_{i-jt-1} = 0 \right) = \theta_3
\end{aligned} \tag{3.22}$$

Durlauf demonstrates with simulations that the model is non-ergodic when the θs are below 0.45. This implies that the steady state will be path dependent. In other words initial conditions do not characterize a global and unique probability distribution for technology choices over the long run. This theory implies that the vagaries of history may bring some countries to poverty traps. It also suggests that long run steady states may be very hard to predict.

The models that I have reviewed provide a broad picture of the types of models that can be constructed to analyze social interactions and adoption decisions. Young's model illustrated the effects of non-cooperative behavior in determining suboptimal equilibria. Follmer and Durlauf's models provided insights on the importance of social spillovers in determining convergence to an optimal or suboptimal equilibria. The model that I develop in the next section will emphasize the role of network structures in equilibrium determination. Undoubtedly, these models have several limitations. One limitation is that the set of assumptions required to be able to apply some of the main theorems regarding graphs and random fields are highly restrictive. For example, most real economic processes of social interactions are not likely to evolve in lattices or in graphs that are fully connected. Also, utility functions and pay-off functions are likely to be more complicated than the ones explored here. Finally, with these models, I have not addressed the issue of how agents learn and how the social network affects this learning process. Nonetheless, the insights derived from these models are useful to understand the simulated dynamics of the more complex ones.

5. Network Typologies and Technology Diffusion

In this final section, I introduce a simplified version of the model of technology diffusion used in this research. It should become apparent that the model, as described here, ignores several features that I have considered important determinants of the technology diffusions process: learning and

knowledge spillovers, and cooperative behavior. My main purpose with this simplified version is just to understand how network typologies affect technology choices, and therefore economic growth.

There is a growing literature on the dynamics of networks that basically looks at how networks evolve as a function of agents' choices. There are two streams in this literature: models based on random graphs (see Blume, 1997; and Durlauf, 1997), and agent-based simulation models (see Epstein and Axtell, 1997). Here, I take classes of networks as given. A class is defined by the statistical process that generates the connections between a given population of agents, that for simplicity I assume is independent of agents' choices and their preferences. The main rationale for this shortcut is that my interest lies on how classes of networks affect the dynamics of the economy, and not in how they evolve. Indeed, the focus of this research is to understand how to better design policies to promote sustainable growth in the developing world, and how policy choices respond to network structures. Surely, networks evolve, but it is unlikely that they will shift from one class to another overnight. Hence, the policies that we implement today are based on classes of networks observed today.

I start with the assumption that a developing economy can be represented by a graph G(V,E). What is different in this graph, compared to other graphs in the literature, is that the two dimensions of the space of vertexes, V, have precise economic interpretations. The first dimension (K) can be viewed as a one-dimension social space. The second dimension (C) is simply a one-dimensional geographic space. Hence a vertex of the graph is a vector $i=(k_i,c_i),\ k_i \in K,\ c_i \in C,\ V=K\times C$ that characterizes an agent in terms of its ownership of capital and its location in the geographical space. As usual, I define the neighborhood of an agent i by the set $v(i)=\left\{j \in V; \{i,j\} \in E,\ i \neq j\right\}$ (i.e., the set of other vertexes that share an edge with i).

Agents in this economy represent producers of a composite good that can be viewed as total GDP. As in Durlauf (1997), producers are assumed to choose

production technologies in order to maximize profits. These choices determine aggregate production.

The set of technology choices is W and the state of the system is defined by the set $\tilde{\omega}$ of choices w_i observed at a given point in time. We have $\tilde{\omega} \in \Omega$ where Ω is the set of all possible configurations of choices of the system. For simplification, I assume in this section that $w_i = \{1,-1\}$, and define the profit function for each producer i using technology w_i by:

$$\pi(w_i) = pf_{w_i}k_i - c_{w_i}k_i + w_i \sum_{j \in v(i)} J_{ij}w_j \, , \tag{3.23}$$

where f_{w_i} is the production function under technology w_i that verifies standard curvature assumptions, p is the price of output, k is the amount of capital owned by the producer (which determines its position in social space), and c is the cost of operation of the technology. c includes the costs associated with the type and quantity of labor required to operate the technology (the model presented in Chapter 5 makes more specific statements regarding the operating costs of the technology and the demand for labor). The term J_{ij} measures the *importance* of the connection {i,j} and becomes a proxy for the level of social spillover effects (the spillover effects in the model presented in Chapter 5 have more structure and realism). In what follow I assume that the population of agents is constant over time. This is a strong assumption, unfortunately necessary for analytical purposes.

I first look at the case where J_{ij} =0 for all i and j so that there are no spillover effects. I also assume perfect information. Then the optimal choice for producer i is:

$$w_i = \arg\max \{\pi(w_1), \pi(w_{-1})\}, \tag{3.24}$$

Thus, an agent will compute profits under each condition and choose the one that maximizes profits. Notice that if $f_1(.) > f_{-1}(.) \wedge c_1 < c_{-1}$ all producers will choose technology 1 and if $f_1(.) < f_{-1}(.) \wedge c_1 > c_{-1}$ all producers will choose

technology 2. Then the non-trivial case that I consider is the one where $f_1(.) > f_{-1}(.) \wedge c_1 > c_{-1}$. This case implies that technology 1 is more productive but is also more costly. In this case, the choice of technology 1 implies:

$$\frac{f_1(k_i) - f_{-1}(k_i)}{k_i} \geq \frac{c_1 - c_{-1}}{p}, \tag{3.25}$$

From this condition I derive the following proposition.

Proposition 1: Given an economy G and profit functions defined by (3.23), there exists $f_{-1}(.) < f_1(.) \wedge c_{-1} < c_1$ and levels of capital $k_{\min}$ and $k_{\max}$ such that agents i choose technology 1 if $k_{\min} \leq k_i \leq k_{\max}$ and the resulting choices constitute an equilibrium (see proof in Appendix 8.5).

Proposition 1 states that if technology 1 is more productive and not too expensive, some of the agents will choose it, and that these agents are likely to be in the "middle" of the distribution of agents along the social dimension. Because I have implicitly assumed that the costs of operating a technology are not related to geographic regions, the location of the agent along the geographic dimension does not affect the choice.

I now introduce spillover effects. To analyze the resulting dynamics, I make the following assumptions regarding the adjustment process and the connectivity of the agents (again these assumptions are relaxed in Chapter 5).

Myopic Sequential Adjustment Process (MSAP): At time zero, all agents believe that there will not be any spillovers effects. Hence, at the beginning of time t=1, equilibrium is given by Proposition 1. Then, after having observed the choices of their neighbors, at the end of period 1, agents update their decisions for time 2 (notice that this excludes any type of strategic behavior or forward looking behavior). The process continues until no more changes are made.

Complete Connection Sets (CCS): Technology characteristics and connection sets are such that for *any* agent, there is potentially a set of connections

such that technology 1 is the preferred choice. Basically, the agent has the potential to be connected to enough users of technology 1, as to make that technology the optimal choice.

The question that I analyze is: where does the economy converge? The answer depends exclusively on the relative productivity and costs of the technologies and the type of network typology. The following proposition holds:

Proposition 2: Given an economy G with profit functions (3.23), MSAP, and CCS, there exists a set ξ of typologies E such that the economy will converge to a high productivity equilibrium, and a set ξ' of typologies E where the economy will converge to a low productivity equilibrium.

Proposition 2 states that in this economy, both high productivity and low productivity equilibria are possible, and that which one is observed depends on *how the agents are connected.* In principle, if for a given economy we observe (3.23) and the network typology, we could be able to predict whether a given technology will diffuse or collapse. Unfortunately, it is very unusual to be able to observe the full typology of a network. Usually, what we have is some estimate of the likelihood that two given agents establish a connection (see for example the Ethno-Linguistic Fractionalization index in Sub-sections 3.2 and 3.3).

Then what we really would like to be able to do is to associate classes of network typologies to the statistical processes governing their creation. If this can be done, then we can ask the question of what types of statistical processes are more likely to generate a typology that ensures that the economy converges to a high productivity equilibria. By doing this, we can expect to answer questions such as: for what values of the ELF index is convergence to a high productivity equilibria more likely?

In most of the literature, the predominant assumption is that agents are more likely to interact with other agents if they are close, and less likely to interact with other agents if they are far apart. Distance can be social distance or geographic distance. In principle, then, the probability that two agents will establish a connection can be represented by:

$$\Pr(i \leftrightarrow j) = \phi(\beta\|i - j\|), \tag{3.26}$$

where $\phi()$ is the statistical process driving the network structure. In what follows, I will assume that all connections have the same importance.

The question that I address is whether process $\phi(\beta)$ can generate network typologies that tend to drive the economy to a high productivity equilibria. Morris (1997) addresses a similar question. The idea is to show that the statistical process can generate typologies where we can construct with positive probability sequences of sets S'(t) of new adopters of given technologies, conditional on the set of previous adopters S(t-1). This does not prove that the economy will converge to full-dominated equilibria, but just that the number of adopters can grow with positive probability until *some* equilibria is reached.

Some preliminary definitions are required to tackle this problem.

Definition: *i-support*. I call 1-support the set S(1) of agents in t that chose technology 1 at time t, and -1-support the set S(-1) of agents that choose technology -1.

Definition: *Reservation connectivity set*. I call reservation connectivity set for agent i∈S(-1) the set **I** of vectors $\iota = (x_\iota, y_\iota)$ with $\{|v_j(i)| = x_\iota; j \in S(-1)\} \wedge \{|v_j(i)| = y_\iota; j \in S(1)\}$ that solve (3.25). The set **I** gives the configurations of connections that will lead agent i to adopt technology 1 at time t+1. For example, one element of **I** could be (1,3), that states that if agent i is connected with 1 element in S(-1) and is also connected with 3 elements of S(1), then he/she will switch to technology 1.

The following three propositions follow:

Proposition 3: Given economy G, profit function (3.23), and MSAP and CCS with best-response-dynamics, choices are irreversible.

Proposition 3 states that once an agent has switched from technology -1 to technology 1 at time t, he/she will not have any incentive to switch back at time t+1. Indeed, at that time, in the best case scenario he/she will have a number of connections with users of technology -1 that is equal to the number of connections that he/she had in t-1 and that justified switching. On the other hand, his/her connections with users of technology 1 could remain the same, but most likely would have increased.

Proposition 4: There exists h such that if $\beta > h$ the probability of observing a network with non-empty reservation connectivity is greater than observing a network with empty reservation connectivity.

Proposition 5: There exist a unique β^* such that the probability of observing a typology consistent with non-empty reservation connectivity is maximized.

Proposition 4 states that there are statistical processes that are consistent with typologies that generate high or low productivity equilibria with positive probability. This result is complemented by proposition 5 that states that the relationship between β^* and the probability of observing a typology that will converge to a high productivity equilibria is non-linear. Indeed, economies with $\beta > \beta^*$ or $\beta < \beta^*$ will have lower probabilities of convergence.

Highly connected societies are not necessarily more prone to development than poorly connected societies. The intuition is that in the former, inertia is high, and in the second there are not sufficient positive spillovers that can emerge.

6. Conclusion

This chapter has introduced the concept of social capital and emphasized its importance in the process of technology diffusion and growth. In particular, producers' network structures will determine the level of knowledge spillovers as well as the emergence of cooperative behavior, and will therefore affect adoption decisions. I have also illustrated how the Social Interactions

approach can be useful to formalize and model the concept of social capital. By doing so, the approach offers the opportunity to improve the formalization of the technology diffusion process and make policy analysis decisions based on these models, more sensitive to diffusion externalities. Probably one of the most important insights from these models is that whether economies converge to socially optimal states depends not only on initial conditions, in particular network typologies, but on the vagaries of history as well. Fortunately, governments may try to influence positive outcomes. The chapter has also showed that the effect of networks on the technology diffusion process can be studied in terms of the statistical process that generates the network. In particular, it is likely that low and very high connectivity are associated with lower diffusion rates.

In the next chapter, I will use the main insights from this chapter to construct an agent-based model of technology diffusion and growth. I use simulation techniques to answer three questions: a) how do network typologies affect economic growth; b) what type of policy interventions can be implemented to increase the likelihood of an economy to converge to a sustainable path; and c) how do these policies change as a function of the network structure of the economy.

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[1] At the micro level, social networks may also be simple proxies for the concept of social support. For example, a well-known result is that health indicators for a low birth weight are correlated with indicators of social support (see Plebey et al., 1997 for a study on Guatemala). This, however, is not the role that I emphasize in this research.

Chapter 4 - Policies to Promote Sustainable Development

1. Introduction

I have argued that sustainable growth is about preserving productive capacity through an efficient inter-temporal allocation of human, produced, and natural capital. There is a myriad of policy instruments that could be used to influence this allocation. Indeed, it is clear that any type of policy intervention (e.g., trade policy, social security and welfare reforms, tax reform, debt re-negotiation, monetary and fiscal policy, or minimum wage policy) will in one way or another have impacts on consumption, savings, and the demand for natural resources, and therefore growth and sustainability. Then, ideally, one would like to consider the full space of policy instruments and policy choices available to policymakers, and define a global development strategy that ensures that the economy converges to a sustainable path, given a known set of relationships between the policy instruments and the dynamics of the economy. This is of course impossible from a computation standpoint.

In practice, the topic of "sustainable development" is a much more specialized one. If one looks at the homepage of the World Bank, sustainable development is only one of several topics related to economic and social development. Others include health policy, rural development, or social security reform. Sustainable development has been mostly associated with environmental policies, which can be classified into four categories: a) policies that use markets; b) policies that create markets; c) policies that regulate markets; and d) information-based policies. Those working on sustainable development issues have had a tendency to focus on the analysis of these types of policies without systematically taking into account how they affect and are affected by other government policies. The same is true for those working on macroeconomic policies. Even today, ministries of finance and monetary authorities pay scant or no attention to environmental issues, such as the exploitation of natural resources, or the damaging effects of environmental pollution. My hypothesis is that in many cases (i.e., for many assumptions about the structure of the economy and its linkages with the environment) a robust intervention to promote sustainable development will require at least some degree of coordination between environmental policies, policies that

affect investments in human and produced capital, and policies that affect the diffusion of new technologies. The main reason is that welfare-increasing choices of environmental policies depend for example on the expected dynamics of investments in human capital and the technological factor. If one believes that neither investments in human capital nor the diffusion of new technologies need to be regulated, then good environmental policy would mostly depend on policymakers' ability to deal with uncertainty regarding market driven dynamics of the stock of human resources, and, for example, the emissions intensity of the economy. Most analysts will agree, however, that both investments in human capital and the diffusion of new technologies may be subject to externalities that require government intervention. This implies that the environmental externality - that has received most of the focus in the debate about sustainable development - is not the only externality that should be addressed by policies designed to promote sustainable growth.

This chapter discusses the key environmental, macroeconomic, and technology policies that should be considered when designing and implementing strategies to promote sustainable growth. The chapter is organized into four sections. Section 2 introduces the policy problem and describes the objectives, the constraints, and the type of macro policy levers involved. Section 3 is concerned with the inter-temporal allocation of natural resources. Section 4 reviews the type of environmental instruments available to policymakers. Section 5 discusses technology instruments, while Section 6 analyzes the linkage between macro policies and investments in produced and human capital. Finally, Section 7 summarizes the main ideas.

2. Promoting Sustainable Development: an Inter-temporal Optimization Problem

From a macro perspective, one can abstract and assimilate the problem of promoting sustainable growth to the following dynamic optimization problem:

$$\begin{cases} \max_{a_t, n_t, Sb_t, C_t} : \sum_t (1+r)^{T-t} \left\{ L_t \dfrac{(C_t / L_t)^{1-\tau}}{1-\tau} \right\} \\ s.t. \\ GDP_t = f(K_t, H_t, n_t; \theta_t)(1-d_t) \\ K_t = K_{t-1}(1-\delta_k) + I_{t-1} \\ H_t = H_{t-1}(1-\delta_h) + h_{t-1} \\ N_t = N_{t-1}(1+R) - n_t \\ S_t = GDP_t - Sb_t - C_t \\ I_t = a_t S_t \\ h_t = (1-a_t) S_t \\ \theta_t = g(H_t, n_t, K_t, Sb_t) \\ d_t = 0 \;\; if \;\; N_t > \delta_1; \;\; d_t = \delta_0 \left[\dfrac{\delta_1}{Nt} \right]^{\delta_2} \;\; otherwise \end{cases} , \qquad (4.1)$$

Hence, the goal is to maximize the present value of a utility function that depends on consumption (C), by using three macro policy levers: the level of technology incentives (Sb_t), the share of domestic savings net of technology incentives that goes into produced capital (a) and human capital (1-a); and the quantity of natural resources consumed in a given period (n). There are several constraints on policymakers' choices. First, the total level of output (GDP) is given by an aggregate production function that depends on the available stock of produced (K) and human capital (H); the consumption of natural capital (n), and technological factors that I capture through the vector of parameters (θ). The stocks of produced and natural capital depend on how domestic savings (S) are distributed between investments in produced capital (I) and human capital (h) through the control variable a. Savings are equal to aggregate output minus consumption (C) and technology incentives

(Sb). On the other hand, the dynamics of the stock of natural resources (N) is given by the regeneration rate (R) and the consumption of natural resources (n). The vector θ changes as new technologies enter the economy in response to changes in the costs of alternative production factors. Indeed, the diffusion of new technologies modifies the productivity of the different production factors and their elasticities of substitution. These changes are given through some function g(.) that depends on the stock of human and produced capital, the quantity of natural resources that producers are allowed to use (n), and technology incentives (Sb). Finally, environmental damages may occur when the total stock of natural resources is below some threshold δ_1[1].

Problem 4.1 is of course a simplification. Nonetheless, it allows us to think about some the main issues behind sustainable growth. First, sustainability requires some specific distribution of income between savings and consumption, and a specific distribution of savings between produced and human capital. Second, the inter-temporal consumption of natural resources needs to be sensitive to changes in technological factors and the economic cost of potential damages resulting from environmental degradation. Optimal consumption and savings schedules are not necessarily unique.

One of the important questions is whether market mechanisms are sufficient to converge to optimal consumption and investment schedules. Few will argue that in most of the cases, this is unlikely. For instance, we know that several market failures affect the consumption of natural resources. Not only may market prices not reflect current social cost, but we may also have a situation where, given myopic consumers, prices today do not reflect the opportunity cost of lacking the natural resource in the future. Most policymakers will also agree that public regulation of investments in human capital, in particular in the education and health sectors, are required given inequality problems and externalities resulting from social spillovers. Finally, there are several reasons why private savings may differ from optimal social savings. Some of them include for example short planning horizons, high discount rates, lack of risk sharing instruments, insufficient government savings, or imperfections in global financial markets. In the latter case, increasing the savings rate of a country can reduce dependence on foreign

capital, and therefore reduce the risk of financial crisis. However, this benefit is not taken into account by private decision-makers, thus generating a market failure (see Schmidt-Hebbel and Serven, 1999).

In essence, government may require to regulate the dynamics of all those factors that are important to promote sustainable growth. The next sections discuss alternative instruments and the main issues involved in their utilization.

3. How to Consume Natural Resources over Time?

One question that policymakers need to address is whether to regulate the consumption of alternative natural resources over time (i.e., whether to regulate the dynamics of the depletion rate). Regardless of social costs (e.g., environmental damages) associated with the consumption of the natural resources (e.g., carbon emissions), there is an inter-temporal trade-off between consuming the resource today and consuming the resource in the future[2]. This is a complicated problem, since the researcher needs to analyze simultaneously what is the appropriate consumption schedule, and also what is the most effective instrument. Indeed, choosing the dynamics for the quantity consumed of a given natural resource implicitly determines the dynamics for its price. Thus, a policymaker may emit permits to ensure a given consumption schedule, or alternatively, the policymaker can chose to reinforce the implicit price through taxes. Unfortunately, in the presence of uncertainty, these two types of interventions are not equivalent (see Section 4). In this sub-section, I am going to focus on the analysis of quantities. Other policy instruments are discussed in Section 4.

It seems that the first researcher to formally address the question of how to use a *finite* stock of natural resources was Hotelling (see Hotelling, 1931). Hotelling first provided conditions under which a competitive market could guarantee an optimal consumption of the stock of natural resources. He also showed that monopolists generate extraction rates that are "too slow" from a social point of view. This is because monopolists take the intertemporal

demand for natural resources as given and therefore are able to implement higher future prices. Thus, they have incentives to postpone extraction. As suggested by Robert Solow (see Solow, 1974a), monopolists should be the best friends of environmentalists.

Four decades after Hotelling's seminal paper, the question of which is the optimal depletion rate re-appeared in the table of theoretical economists (see Solow, 1974b; Nordhaus, 1974; Dasgupta and Heal, 1974; Weinstein and Zeckhauser, 1974; Lewis, 1979; Dasgupta and Stiglitz, 1981; and Dasgupta et al. 1982, among others). The problem is similar in nature to the problem of when to switch to a new technology. Owners of natural resources need to decide whether to extract today or wait to extract tomorrow. The stock of any natural resource is an asset. Therefore, in equilibrium, its rate of return should be equal to the rate of return of other assets in the same risk family. Hence, the value of the stock of natural resource, should grow at a rate equal to the interest rate. However, we know that the value of an asset is equal to the present value of expected profits. In the case of natural resources these profits are the value of total sales minus extraction costs or the net price of the natural resource. It follows that, in equilibrium, the net price of the natural resource should grow at a rate equal to the market interest rate. This does not imply that the price of the natural resource grows at a rate equal to the interest rate. Indeed, the growth rate of the net price is given by a weighted average of the growth rate of the market price and the growth rate of extraction costs. If extraction costs are falling, then the market price can be doing almost anything (stay constant, fall, or increase). However, if extraction costs are rising, the market price is also rising[3].

Notice that within this framework optimal extraction rates depend on expectations about market prices and extractions costs[4]. Both of these expectations are of course affected by expectations about technological changes in the supply and demand sides of the market for natural resources. If owners of natural resources expect higher future prices, then natural resources become a great mechanism to hold wealth and extraction will be postponed. On the other side, if prices are expected to fall, extraction rates should accelerate. It is usually assumed that market prices should be expected to increase up to the point where demand shuts-off. As stated by

Solow: "At that moment, production falls to zero. If flows and stocks have been beautifully coordinated, through the operation of future markets or planning boards, the last ton produced will also be the last ton on the ground".

The question of how to consume a natural resource when a new technology that substitutes for its use is available, although initially too costly, was addressed by Nordhaus (1974). Nordhaus calls the new technology, a "backstop technology". This technology does not have scarcity rent and is able to operate as soon as the market price rises enough to cover its extraction costs. At that point, the price of the natural resource stops rising. Nordhaus shows that the date when the new technology enters the market coincides with the date when the last unit of the natural resources has been fully consumed. Nordhaus, however, assumes that the existence of the new technology and its operation costs are known with certainty. Yet, decisions about depletion rates are based on *expectations* about prices and technological innovations. Dasgupta and Stiglitz (1981) study a model with two technologies: an old technology that depends on the use of non-renewable resource, and a new technology that does not require the natural resource. This last technology, however, does not exist at time 0 and is assumed to be invented at some date T>0. The authors analyze the optimal consumption of natural resources, first for a known T, then for an unknown T. They derive two fundamental propositions. The first proposition refers to the case where T is known. In this case, the stock of natural resources is fully depleted between time 0 and the time of adoption of the new technology (that does not necessarily coincide with the date of invention). The fundamental idea is that the cost of a natural resource will rise up to the point where the new technology is profitable and that the date of adoption coincides with the date of full depletion of the natural resource. The date of adoption depends of course on its cost. The second proposition deals with the case where the invention date is unknown. In this case the rate of extraction ought to be chosen in such a manner that the economy possesses a positive stock so long as the invention has not occurred. Whether depletion rates are higher than in the case where T is known depends on the initial stock of natural resources and the price elasticity of demand. If at high prices of the natural resource the elasticity of demand is "high", then for high initial levels of the stock

of natural resources there is higher conservation while for low levels of the stock there is profligacy! In the case where the price elasticity of demand is low for high prices, then there is less conservation for low and high initial stocks of natural resources, and higher conservation for middle size stocks. In this problem, there are not certainty equivalent rates of invention. However, there are certainty equivalent discount rates[5].

Full depletion of the natural resource, however, is not always associated with optimal depletion. Lewis (1979) investigates conditions required to observe exhaustion of a natural resources. A necessary condition is that the resource can be extracted profitably as the stock diminishes. Lewis writes:

"One factor working against exhaustion is the depletion effect which is manifested in the higher marginal recovery costs encountered as the resource stock is depleted. For the example of mining, depletion effects occur because lower grade ores are encountered as more of the resources are extracted. Likewise, depletion effects are observed in the harvesting of a fishery because it is more difficult to locate and capture the fish as the stock becomes less dense. Consequently, some portion of the resources may be left unexploited if depletion effects cause further utilization of the resource to be unprofitable."

This implies that exhaustion of the natural resource is a characteristic of the extraction technology. Lewis shows that if the natural resource production technology is convex, resource recovery is profitable for any positive stock despite depletion effects. Lewis writes: "A non-replenishable resource stock will either be exhausted in finite time or will be gradually driven to zero, given normally convexity assumptions, regardless of whether the resource is competitively exploited or centrally managed".

Up to this point, I have been discussing cases where the natural resource is not essential. This results from the fact that the new technology is assumed to generate output without using the natural resource. When the natural resource is *essential*, a positive level of output requires a positive stock of the natural resource. There are two cases that one can consider. The first refers to a non-renewable resource. In this case, sustainability is not an issue; sooner or latter the stock of the natural resource will be fully depleted and the economy will collapse (see Dasgupta and Heal, 1974)[6]. The

non-trivial case considers a renewable resource. In this case, sustainability implies stabilization of the stock of natural resources. Indeed, it does not make sense to accumulate natural resources forever. It does not make sense either to consume all natural resources since output then will be zero. Therefore, in this case, optimal consumption implies stabilizing the stock of the natural resource.

In practice, policymakers seldom regulate the inter-temporal allocation of natural resources, at least within a welfare-maximizing strategy that evaluates the trade-off between consumption today and consumption in the future. Most regulations, through quotas or price subsidies, are implemented with different, mostly short term, goals (e.g., increase fiscal revenue; or simply promote the development of the industrial sector). As discussed in this section, most theoretical models predict that markets can generate an efficient inter-temporal allocation of natural resources, even in the presence of uncertainty. Nonetheless, these predictions are derived by assuming that agents' expectations about future prices are generally unbiased. This may not be the case, at least during given periods of time. Therefore, consumption of natural resources may be too fast or too slow from a social point of view. This does not imply that the government should automatically regulate this inter-temporal allocation. The implication is that governments and research in general should invest resources in trying to evaluate current patterns of consumption, and when necessary advise on potential mechanism to adjust these patterns. Chapters 5 and 6 will address this issue.

4. Environmental Policies

While the previous section discussed policy issues related to market failures resulting from the inter-temporal distribution of natural resources, here I address failures related to environmental damages. Environmental policies address these failures. In 1989 the Organization for Economic Co-operation and Development (OECD) identified more than 100 different types of policy instruments used to regulate the impacts of economic activity on the environment (see Huber et al., 1998). In this section I review some of these instruments. My discussion relies heavily on the World Bank study on Sustainable Growth (see World Bank, 1999a), and is organized around four types

of policy interventions: a) policies that use markets; b) policies that create markets; c) policies that implement environmental regulations; and d) policies that provide information and engage the public. Table 4.1 describes the use of some of the instruments considered in this section across Latin American countries.

	Barbados	Bolivia	Brazil	Chile	Colombia	Ecuador	Jamaica	Mexico	Peru	Trinidad and Tobago	Venezuela
Credit Subsidies	●		●		●	●		●			
Tax/ Tariff Relief	●		●	●	●	●	●				●
Deposit-Refund Schemes	●	●	●	●	●	●	●	●	●	●	●
Waste Fees and Levies	●	●	●	●	●	●	●	●		●	●
Forestry Taxation		●	●		●						●
Pollution Charges			●		●		○	●			
Earmarked Renewable Resource Taxes			●		●	●					
Earmarked Conventional Tax Levy			●		●			●			
Tradable Permits		○		●				○			
Eco-Labeling		●	●	●		●		●			
Liability Instruments		●			●					●	
● In Place											
○ Being Introduced											

Table 4.1: Market-Based Instruments Are Gaining Wider Application.

Source: Huber et al. (1998).

4.1 Policies that Use Markets

Among the most powerful policies for improved environmental management are those that use the market and price signals to make the appropriate allocations of resources. Price distortions arise in two ways. First, many subsidies actually reduce the cost of overexploiting or polluting the environment. Second, market prices generally reflect only private costs, ignoring the damage inflicted on others by pollution emissions. Using markets therefore involves moving towards free market prices on one hand, and moving beyond free market prices on the other. These policies are attractive because they are relatively easy to implement and manage, and because they may have positive fiscal effects on state revenue - by reducing subsidies and generating revenues from pollution taxes. Fiscal effects may not be negligible. Indeed, the World Bank estimates that the value of damaging

subsidies totals over USD 249 billion per year in the developing world (see Dixon et al., 1998, Chapter 4).

Several categories of policy instruments that use markets are available. *Subsidy reductions* are currently one of the most popular. There are many examples of successful subsidy removals in the developing world. Many countries have eliminated subsidies in energy and water pricing. Others like Bangladesh and Indonesia have removed fertilizer and pesticide subsidies, while countries like Brazil have removed subsidies that lead to excessive land clearing.

Another type of instrument that uses markets is *user fees*. This recognizes the fact that while many individuals derive important benefits from the use of the environment, some may pay little or nothing for this right, which leads to poor levels of services or overuse resources. User fees are a mechanism to capture part of this benefit. Hence, many countries protect recreational areas through user fees. For example, Costa Rica and Ecuador protect their volcanoes, beaches, and rainforests. Also several of the East African countries with safari businesses are actively using user fees to protect the environment and generate additional government revenue.

A third important instrument is *pollution taxes*. This instrument is used to internalize the cost of negative externalities, resulting for example from pollution. While theoretically appealing, this instrument is unattractive from a political point of view. Indeed, in less developing countries economic agents are often reluctant to transfer revenue to inefficient governments[7]. Yet, countries such as the Netherlands have managed to impose environmental taxes on emissions. Taxes on the use of water and energy are also becoming popular in the developing world. The benefit of this policy is that, by sending the signal that using a resource imposes costs on others, environmental taxes serve both as an incentive to be more efficient in resources use (decreasing total demand and reducing environmental damages), and generate revenue.

Other instruments that use markets include performance *bonds and deposit-refund systems*. In both cases, a financial bond or deposit is used to

guarantee compliance with a desired outcome, such as meeting environmental standards. This instrument has been used in countries like China (Taiwan) to promote replanting of forest land after harvesting, or to correctly dispose of waste products.

Probably the main limitation of these policies is that they require reasonably free and competitive markets (i.e., require markets where the only failure is the environmental externality) that in many cases are not available. For example, pollution taxes in a monopolistic market can reduce social welfare. The implementation of these types of policies also requires relatively mature institutions where corruption is not the prevalent norm. If these conditions exist, however, the optimal tax or subsidy can be computed as the difference between the optimal price of the natural resource (p_t) and the observed price. If p_t is greater than the observed price, subsidies would need to be removed or taxes implemented. Notice that it is possible that during a given period of time, p_t could be lower than the observed price, suggesting that subsidies should be implemented.

4.2 Policies that Create Markets

One of the main threats to sustainable growth is the absence of markets for environmental resources and services. Establishing property rights, privatizing, decentralizing, and generating permits are examples of policies that contribute to the creation of these markets.

Establishing *property rights* for land, water and even forests may constitute an important incentive for better resource management. For example, giving forest in concession through long-term contracts provides incentives to exploit natural resources in a sustainable manner.

Privatization and decentralization constitute a mechanism to move the management of natural resources away from the public sector. Indeed, very often - in part as a result of political constraints - natural resources managed by the public sector (e.g., water) are under-priced. The private sector, on the other hand, has incentives to generate revenues in the present

and make investments to generate revenues in the future. Many critics argue that the private sector in the developing world is not ready to handle the responsibility. This may be the case in many instances. It is also true that the list of success stories is growing. For example, in the Ivory Coast, increasing the risk-share of the private sector has dramatically improved access, quality, and economic and environmental performance.

Hence, it is possible that property rights or privatization are sufficient to bring the observed price of natural resources to the optimal price p_t. In this case, the optimal price will also be the market price. However, if the market price turns out to be below p_t, instruments such as taxes may be required to complement privatization.

Tradable permits involve the explicit creation of a market for environmental resources. Permits to use natural resources and environmental services are distributed among users. The permits have the potential to be traded. This implies that holding a permit has an opportunity cost (the opportunity cost of selling the permit). Hence, permits will change hands until their marginal cost (i.e., their market price) is equal to their marginal benefit (the revenue generated by consuming one additional permit worth of natural resources), leading to an efficient use of natural resources. Tradable pollution emission permits are probably the best known example of market creation. This type of permit has been used for example in Singapore to control the emission of ozone-depleting substances. Probably the main limitation of this instrument is that the initial distribution of permits has important impacts on the distribution of revenue. Hence, identifying a politically viable distribution policy may be a complicated and often unsolvable problem.

Often the welfare effects of taxes and permits are taken as equivalent. If a policy maker sets a tax tx in a market where the equilibrium is given by the price and quantity (p0,q0), it will generate a new equilibrium (p*=p0+tx,q*). If, the policy maker fixes q* through permits, the market price will also be p* and therefore the price of the permits will be p*-p0=tx. This equivalence vanishes, however, when we face uncertainty regarding the shape of the demand and supply functions in the market. In this case the effect of a tax or

permits becomes uncertain. Ex-ante, a tax will be associated with a probability distribution of the market quantity. On the other side, a given level of permits will be associated with a probability distribution of the market price. Weitzman (1974) showed that when the demand function is elastic (i.e., "small" changes in price are associated with "big" changes in quantity) policy makers should prefer permits. On the other side when the demand function is inelastic ("small" changes in quantity are associated with "big" changes in price), policymakers should prefer taxes.

4.3 Environmental Regulations

Standards, bans and quotas are probably the most popular instruments to handle environmental problems. This is an interesting paradox, since among all the categories of instruments that we are discussing, regulations tend to be the least efficient. The main reason is that in many cases this type of regulation discourages innovations that have the potential to reduce pollution in a more efficient way. Also, the success of these policies critically depends on the credibility of governments' environmental policy (i.e., the credibility of sanctions). In many cases in developing countries, these sanctions are not adequately reinforced - either because of lack of resources or simply because the authorities that regulate the policy are corrupt. The failure of CO_2 emissions regulations for vehicles program in Quito, Ecuador is an example. Faced with the choice between investing in emissions reduction systems or bribing the regulator, most drivers preferred the latter.

Nonetheless, these types of instruments are in principle easy to administer and monitor. Also, in some cases, they are the only way to proceed. For example, in the case of very hazardous substances, outright bans tend to be the best alternative. Also, when there are relatively few sources of pollutants, market approaches are not feasible. For example, if there are two or three electricity generating stations that emit sulfur oxides, regulatory abatement standards may be cheaper and simpler to administer than pollution permits or pollution taxes. Indeed, it is easier to observe that the standard has been implemented than to periodically measure the quantity of emissions and charge the tax accordingly.

Notice that because producers are heterogeneous, the imposed level of natural resources is for some of them, probably the majority, different from the optimal level at current prices. Hence, some producers will prefer to pay penalties instead of complying with the constraint. One can think about setting the quota as a function of total output, or total capital. Still, because regulators are not able to fully control for heterogeneity, assigned levels of output are likely to differ from levels that would be observed under the optimal tax.

4.4 Information and Public Engagement

Lately, it has been suggested that informing consumers about environmental issues and involving them in the debate about environmental policies is a key intervention to address environmental problems. Indeed, only in a few cases is the government the agent that drives voluntarily an environmental agenda. In most cases, environmental policies result from political pressures from different social organizations.

Information disclosure is a mechanism to help consumers make better informed choices and demand more environmentally friendly goods. Eco-labeling in Australia and energy efficiency labels in the United States are examples of this type of policy intervention. While appealing, the success of this policy depends on two assumptions: the capacity of consumers to process additional information, and the fact that individual preferences are consistent with social preferences. In the case of the United States, it has been shown for example that only 16% of the consumers purchased appliances on the basis of the information provided on the labels (see Du Pont and Lord, 1998). Furthermore, only 30% considered that energy efficiency was important.

A second instrument within this category consists in promoting public participation. This involves including consumers, trade unions, and community groups in the debate about environmental policy. Successful examples of this approach include water user associations in countries such as Argentina, Indonesia, and Mexico. Another example is given by NGOs' involvement in the operation of protected areas in the Philippines.

One of the main limitations of this approach is that marginal population groups are often excluded from the process. Also, in many cases, there is highly unequal distribution of political power among stakeholders involved in the debate (see Treverton and Leveaux, 1998; and Robalino and Treverton, 1997). Furthermore, a necessary condition for the functioning of this system is the existence of capacity in community-based management.

It is not clear how one should link results from a model such as (4.1) to actions of the type discussed in this sub-section. Most likely information-based policy interventions should be complemented by instruments such as taxes or permits. If policymakers observe that behaviors do change in response to the policies, then they could adapt the tax or the supply of permits.

5. Regulating the Diffusion of New Technologies

Technological progress has long been recognized as the main force behind economic growth. Historically, technological progress has also been critical to guarantee sustainability. For example, the emergence and diffusion of new production technologies in agriculture has prevented Malthus' prophesized population starvation (see Malthus, 1798). Indeed, the diffusion of new technologies, in particular production and energy technologies, determine not only the marginal productivity of the inputs that enter the production process (the main sources of economic growth), but also the set of inputs itself, as well as the levels of different types of waste and polluting emissions associated with a given level of output. This idea has recently been captured in the economic literature by models of endogenous growth that include an environment component.

Sustainability in the developing world may require changes in productive structures. Most of these changes may need to be related to the introduction of alternative production technologies that meet three characteristics: 1) are consistent with macroeconomic and social stability (e.g., guarantee full employment, stable relative prices, and do not promote structural inequality); 2) reduce the demand for critical natural resources; and 3) reduce emissions of waste and pollutants that negatively affect the environment.

Overall, there is a wide agreement at the theoretical level that different types of market failures justify government intervention in the area of technological change, not only by allocating resources to the invention of new production technologies and the accumulation of human capital (see for example Lucas, 1988; Romer, 1986 and 1990; and Grossman and Helpman, 1991), in particular technologies that reduce environmental damage (see Byrne, 1997; Lighart and Van der Ploeg, 1994; Bovenberg and Smulders, 1995; Jones and Manuelli, 1995; and Mohtadi, 1996).

5.1 Policies Affecting Invention and Innovation

The rationale for governments' involvement in the invention and innovation processes is that private markets will most likely under-invest in research and development activities. There are two main reasons that explain why this could happen. First, the private sector's discount rates to evaluate R&D investments are higher than social optimal rates. Second, investors in R&D do not incorporate the social benefits of their investments in their calculations.

Hence, the main government intervention to address market failures within the invention and innovation processes is government funding of R&D. In the developed world most of the resources are allocated to areas of technologies labeled high technology or big technologies. These include defense, aircraft, aerospace, and associated industries. The second area in which government R&D resources are allocated is the advancement of science: work funded primarily in order to increase human knowledge, that is to advance scientific understanding of natural phenomena (see Stoneman, 1987).

Technology policy in most countries has favored these types of interventions (see Limpens et al., 1992). Stoneman and Diederen (1994) argue that this emphasis was misplaced. Indeed, the fact that society invests resources in "new technologies", "new knowledge", or "new process" does not guarantee that technological progress will occur even if new technologies are economically efficient. It is the diffusion process that ultimately generates technological change. Furthermore, investments in R&D tend to be constrained by given "technological paradigms" (see Dosi, 1997), and therefore while we may observe a technological transformation in the direction imposed by the paradigm, it may not be the appropriate direction, for example to guarantee sustainability.

Policies to promote diffusion may therefore be important, particularly in the case of developing countries where technological progress depends mostly on the capacity to absorb/adopt technologies from the "North" (see Krugman, 1994). For example, in the initial phases of development, much of the R&D

undertaken in Japan was absorptive, aimed at integrating foreign technologies (see Blumenthal, 1972). More recently, countries such as Brazil, Mexico, India and China view foreign investments by firms from technologically advanced countries as a vehicle for technological transfer.

5.2 Technology Diffusion Policies

Why intervene in the technology diffusion process?

Within the "neoclassical framework", in a stable economy based on market signals, price-oriented policies are considered sufficient to drive the economy towards a sustainable path. Economic agents are expected to make the "right" technology choices at the "right" time, in order to maximize inter-temporal profits. For example, with appropriate taxes, producers are expected not only to reduce the demand for natural resources and emissions of waste and pollutants, but also to induce the development of alternative, more environmentally friendly technologies. If after imposing pollution taxes these technologies do not diffuse, it has to be because they are not cost-effective. Hence, forcing these technologies into the market by means of some type of technology incentive policies would be inefficient. The reader may ask, what about replacing pollution taxes by technology incentives? A first answer would be that the cost of the subsidy should be higher than the cost of the tax (since we have postulated that even when the cost of the original technology is increased by the cost of the tax, the new technologies are not adopted). But even when costs are equal (i.e., producers are indifferent between the original technology with tax and the new technologies with subsidies) taxes should be preferred over technology incentives given distributional issues. Indeed, incentives need to be financed by the whole society while pollution taxes are mostly paid by those generating pollution (this is not entirely true since consumers also face higher prices as a result of pollution taxes).

The basic idea is that producers have relatively easy access to all available technologies, and can switch between technological choices rapidly and with little cost. If the price of an input rises, then firms will move to production configurations that minimize the use of that input. The implicit

assumption is that it is always possible to switch between inputs, and that producers are not constrained in their choices (e.g., by their research capabilities or the skills of their employees). This approach is not outright wrong (see Kemp et al., 1994). Producers do respond to changing inputs prices. A clear example is portrayed by the energy shocks of the '70s (see Lichtenberg, 1985). However, as an approach to the way producers undertake technological change, especially radical or large-scale change, it is very limited.

The benchmark according to which we should evaluate the need for and the effectiveness of diffusion policies is the *welfare optimal diffusion path*. Along this path, the present value of the intertemporal stream of social costs from adoption is equal to the present value of the intertemporal stream of social benefits. Taking the development path of a given technology as given, at any point in this path the benefit from adoption by the marginal user should equal the social costs of producing that additional unit. The literature has identified three types of market failures that may deviate the diffusion of new technologies from this social optimal path: imperfect information, market structure, and network externalities. I discuss each of these in turn.

Imperfect information

Economic agents have imperfect information not only about the dynamics of the characteristics of a given technology and the benefits they can derive from it, but also regarding the dynamics of the economic environment. Imperfect information is then a source of uncertainty (see Grübler and Gritsevskii, 1998). Usually, uncertainty is treated as agents not knowing the "true" parameters of the model that governs the dynamics of a variable of interest, but knowing the probability distribution of these parameters. This type of uncertainty is not necessarily a source of market failure, since on average, agents will be "correct" in their forecast and therefore in their economic decisions[8]. This is the case where expectations are considered "rational". A more severe case of uncertainty is the one where the agents know the functional form of the model that governs the dynamics of the variable of interest, but have incorrect priors about the probability distribution of the

parameters of this model (an even more drastic case of uncertainty is the one where economic agents ignore the model). In this case, expectations will be initially biased, and therefore decisions based exclusively on these expectations will turn out to be inefficient. Obviously, agents will recognize that their forecasts are biased, and will try to update their probability distributions as new information becomes available. Convergence to a rational expectations equilibrium is a possibility, but it is not necessarily guaranteed (see Grandmont, 1998a and 1998b). Whatever the final outcome, economic decisions will tend to deviate from a socially optimum standard during this learning or convergence process.

Potential users of new technologies will face uncertainty at three levels: 1) the dynamics of future prices for new technologies; 2) the characteristics and performance of the technologies themselves; and 3) uncertainty about the dynamics of the economic system, in particular factor prices. Expectations about these three vectors affect technology choices. Indeed, the optimal date of adoption of a technology is given by a profitability condition and an arbitrage condition (see Chapter 5). The profitability condition implies that the present value of net benefits needs to be positive. The arbitrage condition implies that there are no further gains to be made by "waiting" (i.e., the opportunity cost of waiting - the forgone benefits - are higher than the expected benefits). Usually, expectations about the costs of technologies will affect the arbitrage condition. If expectations of future prices are biased upwards, technology adoption rates will be too fast. Similarly, if expectations about costs are biased downwards, adoption rates may be too slow (i.e., agents will prefer to wait).

Market structure

Market structure problems are related to monopsony or monopoly power in technology markets. Although I do not deal with this type of market failure in this research, I briefly review its causes. The problem with monopolists is that they are able to price-discriminate between current and future users of the technology when they can take as given the intertemporal demand for the technology and its intertemporal costs. It has been shown that whether diffusion rates are sub-optimal depends on whether potential adopters are

myopic (i.e., cannot accurately forecast the future). It turns out that myopic adopters will still generate a diffusion rate that is optimal from a social point of view (see Stoneman, 1987). However, for non-myopic agents, diffusion may be too slow.

In the case of the monopsony, many producers of a given technology compete for too few niches. Hence, they face the opportunity cost of losing a niche "forever". In this case, competition for niches will generate diffusion rates that are too fast from a social point of view.

Network externalities

Network externalities pervade the technology diffusion process. Often, potential adopters of new technologies are organized in formal (e.g., production chains) or informal (e.g., association of producers of given products or simply neighbors) networks (see Kranton and Minehart, 1999). When this is the case, technology choices by one member of the network affect the set of choices and constraints of other members, and coordination failures emerge. As we saw in Durlauf's model in Chapter 3, technological complementarities create inter-temporal linkages between the production functions of each node, in ways similar to social increasing returns models (see Durlauf, 1993; Romer, 1986; Lucas, 1988; and Azariadis and Drazen, 1990). When these complementarities are strong enough, coordination failures which affect long-run behavior can occur, leading to low or high output equilibria (see discussion in Chapter 3). There are two major types of spillovers: knowledge spillovers (that will usually affect productivity and operating costs) and infrastructure spillovers (that will mostly affect operating costs).

Which policies can correct failures in the technology diffusion process?

There are two major types of technology diffusion policies: information-based policies and economic incentives. The first are intended to increase the flows of information about new technologies, hence providing awareness and reducing the potential negative effects of biased expectations. The latter

focus on exploiting social spillover effects related to the cost of production, and the benefits of new technologies.

A well documented example of informational policy is the United States Agricultural Scheme (see Rogers, 1983). The main constituent of this policy was a network of agents whose prime function was to educate and inform farmers who were potential users of the new technology on the applicable advances coming form agricultural research. Rogers argues that this policy was extremely successful in the case of the United States but that there were also many examples of failure, particularly among OECD countries. The main characteristic of this policy is the education/information aspect. Others are: demonstration projects and publicity campaigns, all of which also try to increase the flows of information about the nature of the technology and its existence within the economy. Other examples include the demonstration projects in Brazil to promote the use of renewable technologies (see Mahar, 1994; Queiroz, 1993; and Pitchford, 1994).

In the case of financial incentives, classical examples are the United Kingdom government grants to purchasers of digital computers in the late '60s or the implementation of favorable leasing terms for Japanese robot users. In this case, the goal is to exploit the positive spillover effects of the costs and benefits of new technologies that tend to result when the number of users increases. For example, the benefits of using a fax machine depends on the number of users of fax machines. The more the better. Similar phenomena occur with other types of technologies such as operating systems. On the other hand, it has been documented extensively that the total costs of new technologies (capital costs plus operation costs) decrease as the number of users increases (see Christianson, 1995). Capital costs are reduced because by producing more and more units of technology, producers become more efficient (learning by doing). Similarly, operating costs are reduced because, as the number of users of technology increases, so do the flows of information about how to operate the technology better (learning by using). Furthermore, technologies usually require some type of support infrastructure. The per user costs of this infrastructure also decreases as the number of users increases.

Creating absorption capacity

A final type of policy that is often ignored is the creation of absorption capacity. Particularly in developing countries, new production technologies may fail to diffuse, given shortages of high quality labor or infrastructure constraints. Indeed, when this occurs, the cost of adoption tends to be considerably higher given that prior investments in human capital and infrastructure are required. Given high discount rates, private investors may be unwilling to undertake these investments. Therefore, the government may have an important role to play in allocating resources fundamentally for investments in human capital.

The degree of development of the financial sector is another important determinant of the absorption capacity of an economy. Indeed, technology adoption decisions usually involve high up-front costs with uncertain future returns. The ability of firms to adopt new technologies therefore depends in part on the existence of a liquid financial sector where resources can be borrowed against the future. In order to keep the analysis focused on the role of social capital and human capital formation, our simulation analysis will ignore the role of the financial sector.

6. Investing in Human and Produced Capital: the Role of Fiscal and Monetary Policies

Any type of policy intervention at the macro level affects in one way or another the environment. These effects have been analyzed in several papers (see Convery, 1995; Munasinghe and Cruz, 1995; Lutz et al., 1994; and Eskeland and Jimenez, 1991). The main message is that positive and negative effects coexist. This suggests that macro instruments should not target environmental goals. Rather, macro policy should be used to achieve goals in terms of the distribution of savings between investments in produced capital and investments in human capital, in coordination with environmental policies and technology policies.

The benefits of diverting resources from current consumption to investments in produced capital are justified as a way to guarantee consumption in the

future. Hence, optimal savings/consumption rates depend on households' preferences between consumption today and consumption in the future. Theoretically, the optimal growth rate of consumption should equal the rate of time preference times the marginal product of capital, net of the discount rate and the growth rate of the population (see Blanchard and Fisher, 1993; and Chapter 6).

The benefits of diverting consumption to increase the stock of human capital have a similar nature. Consumption and investments in produced capital can be reduced today if we expect that investments in human capital will produce higher output and therefore higher consumption in the future. This will occur as a consequence of a higher productivity of labor and capital.

Assume that one has derived the optimal level of investments in human and produced capital, as well as the amount of resources to be used as incentives for the adoption of new technologies. How can we implement these policy recommendations? A first step would be to compare simulated optimal savings rates, with empirical rates. When these rates differ, policy makers should then compute the value of optimal policy instruments associated to optimal savings rates. Three of these policy instruments are the tax rate, the interest rate, and government expenditures. To see how optimal savings rates relate to these three policy instruments, let's consider the basic national account identity:

$$Y = Yd + Tax = C + G + I + X - M, \tag{4.2}$$

that states that GDP (Y) is equal to disposable income (Yd) plus taxes (Tax) and also equal to private consumption (C), government consumption (G), investments (I), plus the current account deficit/surplus given by exports (X) minus imports (M). For simplicity, let's also assume that consumption is proportional to disposable income:

$$C = aYd, \tag{4.3}$$

Then (4.2) can be written as:

$$(Y - Tax)(1-a) + Tax - (X - M) = G + I, \tag{4.4}$$

Identity (4.4) states that total private income minus consumption and the savings from the rest of the world (the current account) are equal to total investments and government consumption. Then if Y, X, M and a are given, and if we assume that investments are a function of aggregate output and the interest rate r, $I = bY - v.r$, then the government needs to manipulate the tax (Tax), its expenditures G, and the interest rate (r) to replicate the recommendations of a model like (4.1). In fact, the government can first set the tax rate such that: $(Y - Tax)(1-a) + Tax - (X - M) = s*$ where s* are total investments in human and produced capital, *discounting those investments in human capital made by the private sector and that are recorded in consumption.* We get:

$$Tax = \frac{s* + (X - M) - Y(1-a)}{a}, \tag{4.5}$$

Then it can manipulate the interest rate to set I=I* where I* is the optimal investment in produced capital. We have:

$$r = \frac{bY - I*}{v}, \tag{4.6}$$

Given the interest rate price stability can be controlled through money supply. Finally, government expenditures will be given by:

$$G = s* - I, \tag{4.7}$$

These expenditures can be desegregated in non-capital expenditures (Gw), that are mostly wages and interest payments, and capital expenditures, that again can be divided in human capital (Gh), and produced capital (Gk) expenditures. It is evident from (4.7) that non-capital government expenditures will be constrained to be zero, given that:

$$s* = Gh + Gk + I, \tag{4.8}$$

The implication is that if a minimum bureaucracy and public infrastructure need to be financed for purposes of optimal social regulation, associated recurrent costs need to be added to s*. This will increase the optimal tax rate. While reducing the government deficit in order to increase domestic savings is a rational policy objective, policymakers need to ensure that these savings are not over-invested in produced capital, or even worse, in increasing the savings of the rest of the world.

As an example, let's consider the case of a country that requires to invest 20% of GDP in produced capital and 10% in human capital (above private expenditures recorded in consumption). Let's further assume that the propensity to consume a=0.9, and that minimum non-capital expenditures are given by: Gw/GDP=0.04. Then from (4.5) we get:

$$\frac{Tax}{Y} = \frac{0.20 + 0.10 + 0.4 + 0.9 - 1}{0.9} = 26.6\%, \tag{4.9}$$

So this government should target a tax/GDP ratio close to 27%. Furthermore, lets assume that the private sector handles all investment in produced capital (i.e., i/GDP=0.20). Then, if we estimate how much the private sector invests in produced capital, we can use (4.8) to compute the required government expenditures/GDP ratio. For illustrations, let's assume that G = g + Ih + Ik, where g are non-capital expenditures, and Ih and Ik are respectively investments in human and produced capital. Let's further assume that I/GDP=0.20 (i.e., the private sector handles all investments in produced capital), and that g/Y=5 is are fixed non-investments expenditures (mostly salaries and interest payments). Then, from (4.7) and (4.8) we conclude that the total government expenditures/GDP ratio is given by:

$$\frac{G*}{Y} = \frac{Gw}{Y} + \frac{Gh}{Y} = 0.04 + 0.10 = 14\%, \tag{4.10}$$

During the past 15 years, we have observed a dramatic change in the type of macroeconomic policies that developing countries try to implement. The main feature of this change has been the rationalization of fiscal expenditures and the tightness of monetary policy, mostly as a result of the implementation of

macroeconomic stabilization programs following the Mexican financial crisis of 1982. Several studies looking at the effectiveness of these policies have been conducted. While some defend these programs as a necessary condition to promote sustainable growth (see Little et al., 1993; and Grellet, 1994; for two excellent reviews), others criticize them, arguing that the benefits from stabilization do not justify the resulting loss in human capital that can threaten sustainability (see Peabody, 1996). Lately, international organization such as the World Bank and the International Monetary Fund are thinking about alternative mechanism to manage the macro-economy. The challenge is to evaluate the impacts of macro instruments not only on prices and current account deficits, but also other dimension of our economy such as investments in human capital and the distribution of income. Hence, net benefits from these policies should consider the present value of the social costs infringed by for example reducing capital.

7. Conclusion

The policy framework that I have developed in this chapter can be summarized in Figure 4.1. The dynamic of green GDP is determined by the dynamics of GDP and the stock of natural resources, while the dynamic of GDP results from the dynamics of the stocks of produced capital, human capital, and the depletion of natural resources. The technological factor determines how inputs are combined in the production process, and therefore also determines the natural resources intensity of the economy. A benevolent policymaker trying to maximize inter-temporal social welfare faces the responsibility of choosing adequate depletion rates, investments in human and produced capital, and technology incentives. Depletion rates will be influenced by regulating the price or quantity of natural resources through environmental policies. They will also be affected, indirectly, by the type of technology incentives that are put in place. Targeted investments in human and produced capital, and technology incentives are financed through domestic savings. The appropriate redistribution of these savings can be implemented through monetary (interest rate) and fiscal policies (government expenditures, and tax rate). In the next chapters of this research, I will develop and apply a methodology that

applies part of this framework to estimate the dynamics of depletion rates for fossil fuels, investments in produced capital, and technology incentives in the developing world. These estimates can then be taken as a reference for the type of targets that should be implemented on the basis of the policies discussed in this chapter.

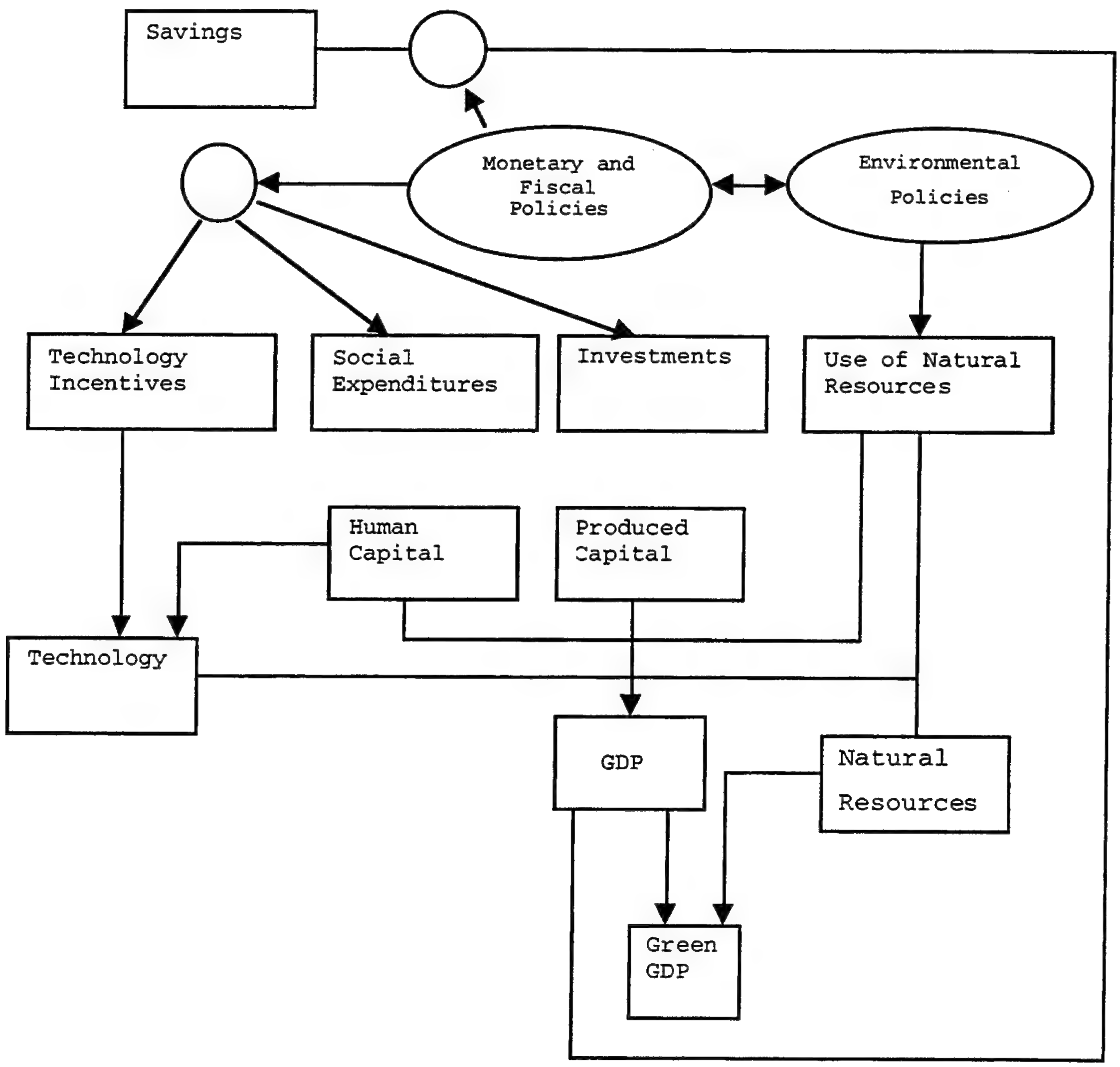

Figure 4.1: A Macro-Framework for the Analysis of Sustainable Development.

[1] Chapter 6 handles the issue of how to solve a problem similar to the one depicted in (4.1) using the agent-based-macro-econometric model for the developing world. As it will become clear, there is no closed form solution to this problem, fundamentally because we do not observe closed form solutions for f(.) nor g(.). Indeed, the model that I use to simulate the behavior of alternative developing countries does not operate with an aggregate production function, nor does it use an aggregate function to determine for example changes in labor productivity. Rather, observed output and factors productivity result from independent agents' decisions about how and how much to produce given observed prices.

[2] Here, I am not considering the case of environmental services (e.g., diverse ecosystems) that generate non-substitutable utility without being consumed and that should be preserved. Nonetheless the question of how much of these natural resources should be preserved is also an important policy question not addressed in this research.

[3] This simplified framework can be useful to think about how markets for natural resources operate, but of course it misses important parts of the story. For example, it is not clear that observed market prices can be used to efficiently allocate the consumption of natural resources over time. Indeed, these prices result from private agents' myopic expectations. If expectations are pessimistic (i.e., if producers expect lower prices in the future), depletion rates will be accelerated thus reducing current and future prices. Thus, pessimistic expectations will be reinforced driving the consumption of natural resources out of equilibrium. As in the case of the technology diffusion, externalities are pervasive in the market for natural resources and regulations may be required to approach a socially efficient distribution of natural resources over time.

[4] Optimal depletion rates are also affected by the type of objective function that one wishes to maximize. Most models have been constructed under a utilitarianism approach. However, some authors have explored what would happen under other types of social functions. One of these social functions was implicitly suggested by Rawls (1971). Basically Rawls argued that social welfare should be measured by the utility of the poorest individual in society. Solow (1974b) studies this proposal. He is able to show that a Rawlasian policymaker will tend to deplete natural resources faster than a utilitarian policymaker will. Indeed, an implication of the Rawlasian framework is that the optimal consumption path is a constant consumption per capita. Assume that this is not the case and that future generations have higher levels of consumption. Then it is optimal to increase consumption today and reduce consumption in the future. This implies that it is optimal to reduce savings today and accelerate the consumption of natural resources.

[5] It is important to notice that all the studies that I have reviewed implicitly assume that at any given point in time only one technology is used. This is a consequence of models that do not incorporate explicitly the process of technology diffusion. As I show in Section 4 when two technologies coexist, the dynamics of the depletion rate may be very different.

[6] Several studies have looked at the optimal consumption of natural resources that would be implemented by a benevolent policy maker. The approach is to modify the standard optimal savings problem within the neoclassical model of growth, in order to introduce a natural resource in limited supply. A typical problem can be written as:

$$\begin{cases} Max: \int_0^T \ln C_t dt \\ \dfrac{dK}{dt} = AK^{1-\alpha}R^{\alpha} - C \\ \dfrac{dN}{dT} = -R \\ N(0) = N_0, K(0) = K_0, K(T) = 0, N(T) = 0 \end{cases}, \quad (1)$$

where C is consumption, K is capital, R is the demand for the natural resource and N is the stock of the natural resource. Setting the Hamiltonian, deriving optimality conditions, and integrating the associated differential equations, it is straightforward to show that the optimal consumption program for this problem is given by:

$$C_t = c_2\left(c_1 + \alpha t\right)^{(1-\alpha)/\alpha}, \quad (2)$$

where c_2 and c_1 are integration constants. Equation (2) implies that the growth rate of consumption will depend on the coefficient α in the production function. In particular if $\alpha>0.5$ (i.e., output is very elastic to change in the use of natural resources) then $(1-\alpha)/\alpha<1$, meaning that consumption will grow at a *decreasing* rate. Not surprisingly, the elasticity of output with respect to the natural resource plays a key role in determining optimal depletion rates. Notice also that the Cobb-Douglas production function used in (1) assumes an elasticity of substitution between capital and the natural resources equal to one. Dasgupta and Heal (1974) have explored optimal depletion rates for the family of CES functions (which include the Cobb-Douglas function as a particular case) with an infinite time horizon. They show that when the elasticity of substitution is less than or equal to one the natural resource is treated as essential. This implies that in the absence of the natural resource production is equal to zero. This is surely an extreme and sad case. I have solved the problem with a finite time horizon at the end of which the stock of natural resources is fully depleted. However, Dasgupta and Heal show that in the case of the infinite time horizon $R_t > 0$ for all t. This implies that the natural resource is not exhausted in finite time. Of course this does not guarantee that the associated level of production and consumption are able to sustain a constant population.

[7] Subsidy elimination policies have the opposite effect. So, taking as given the opposition from those paying the tax or losing the subsidy, subsidy elimination policies tend to have more social support than taxes.

[8] As a matter of fact, this phenomenon does not refer to uncertainty but to risk.

Chapter 5 - A Model of Technology Diffusion, Growth and the Environment

1. Introduction

Chapter 3 was concerned with a theoretical review of the process of technology diffusion and its linkages with the concept of social capital. In this chapter I operationalize these theoretical constructs into an applied model of technology diffusion and growth. As described in Chapter 1, this model has two main components. A module that endogenizes the process of technology diffusion, and a standard one sector macro-econometric model for the developing world, that incorporates an environmental component. The model has been calibrated to address the question of how developing countries should allocate over time investments in produced capital, technology incentives and the "consumption" of carbon emissions. Nonetheless, the model could be used to address other questions regarding sustainable growth, such as the optimal consumption of given natural resource over time.

Before presenting the model I review the current state of the art in applied models of technology diffusion and growth. This way, it will be easier to emphasize the fundamental differences between the model that I develop in this chapter and other models currently available. The chapter is therefore organized into four sections. Section 2 reviews modern *applied* models of technology diffusion and discusses their virtues and limitations. Section 3 introduces my agent-based model of technology diffusion. Section 4 describes the macro-econometric one sector model. Finally, Section 5 summarizes estimates model parameters and presents general results regarding steady state dynamics.

2. Applied Models of Technological Change

The need to model the process of technological change within applied simulation models goes back to the early '70s when the energy crisis forced analysts and policymakers to design and evaluate strategies to reduce dependence on costly imported oil (see Messner, 1997). Two modeling schools

have emerged since then: bottom-up models and top-down models. Bottom-up models emphasize the micro aspects of technological change, in particular the potential for new technologies to reduce their operation costs. Usually, these models are developed within a systems engineering perspective and are rich in the type of micro data that delimit diffusion trajectories (e.g., assumptions regarding the future costs and performances of new technologies). On the other hand, top-down models come from the macroeconometric tradition and operate through aggregate production functions treating technological progress as an exogenously changing parameter within these functions (e.g., the IMF's "Multimod Mark III"; and Laxton et al., 1998) or resulting from exogenously defined changes in capital vintages (e.g., OECD's "General Equilibrium Model of Trade and The Environment"; and Beghin et al., 1996). Early versions of these two types of models include BESOM, the Brookhaven Energy Systems Optimization Model (see Cherniavsky, 1974) and ETA-MACRO (see Manne, 1979). As stated by Grübler and Gritsevskii, "common to both modeling traditions is that the only endogenous mechanism of technological change is that of progressive resources depletion and resulting cost increases" (see Grübler and Gritsevskii, 1998).

Recently, efforts have been made to provide a more adequate representation of technological change, in particular to formalize the role of uncertainty and learning. We have already mentioned in Chapter 4 that uncertainty plays a key role in delaying the adoption of new technologies. On the other hand, learning is responsible for reductions in operation and adoption costs, as well as reductions in uncertainty itself. A model that attempts to endogenize these two elements of technological change is presented in Grübler and Gritsevskii (1998)[1]. The authors explain changes in the operation and adoption costs of new technologies through a learning process that results from commercial investments, research and development (R&D), and demonstration projects in niche markets (the classical learning by doing process). Uncertainty enters the model in the form of randomness in some of the model coefficients (e.g., future demand, learning coefficients). The learning process is "endogenized" on the basis of Wattanabe's empirically derived relationship between investments in new technologies (including R&D and demonstration projects) and operation costs (see Wattanabe, 1995). The model has one decision-maker and three technologies: "existing", "incremental" and

"revolutionary". These technologies differ in their actual costs and the potential for cost reductions (the learning coefficient in Wattanabe's function is uncertain). The goal is to identify the sequence of investments in each of the three types of technologies that will minimize operation costs over a given period of time (set to 200 years). One of the author's contribution is the implementation of an optimization algorithm that solves the stochastic intertemporal optimization problem by sampling points from the *ex-ante* defined distribution of model parameters. Using this algorithm, the author shows that gradual investments in the revolutionary technology, assumed to be 40 times more expensive than the existing technology, are optimal from a social point of view. However, in its current state, the model faces two limitations. First, the problem is solved under the assumption of the existence of a centralized decision-maker who controls the pace of future costs reductions via investments today. More likely, in a real situation, a set of heterogeneous agents will be making technology decisions in a decentralized environment, and therefore cannot directly influence reductions in operations costs. The second problem is that the learning coefficients[2] linking investments to cost reductions *are defined exogenously*. Hence, once the distribution has been defined, the diffusion of each type of technology becomes fully determined: uncertainty vanishes! The model can be used to compute a reference path that the incremental and revolutionary technologies should follow. This is the socially optimal path. Yet, from a policy perspective, it is often valuable to understand the factors that may cause the diffusion of new technologies to deviate from this socially optimal path. In Chapter 3, I proposed that these factors lie at the core of the learning mechanism, specially in the process through which agents generate and share information about new technologies and the macroeconomic environment. These are the processes that, ultimately, one wishes to endogenize.

In the macroeconomic tradition, a novel contribution to endogenize technological change is due to Goulder and Matai (1997). The authors develop a model for the United States where technological progress results from investments in R&D. The fundamental goal is to formalize the market failure discussed in Chapter 3, where the private sector underinvests in research and development. Goulder and Matai show that a combined strategy of taxes and subsidies is the optimal strategy against climate change when social

spillovers are high. Nonetheless, the model ignores the process of technology diffusion and the role of social interactions in affecting this process. Technological progress occurs almost deterministically as investments in R&D increase. Hence, if we know the return to investments in R&D, it is possible to compute which is a socially optimal level of R&D, and therefore the optimal subsidy.

Another model in the macroeconomic tradition is developed in Meijers (1994). Meijers attempts to model the process of technology diffusion within a vintage framework. Hence, he relaxes the pervasive assumption that firms invest only in the state of the art vintage/technology (i.e., diffusion is instantaneous). Nonetheless, Meijers' adopts an epidemic framework. Thus, he defines the share of new investment in each type of technology as a function of the stock of knowledge about every technology. This stock accumulates as a function of the share of the total stock of capital invested in the technology. However, there is no explicit formalization of the adoption decision by individual heterogeneous firms.

The model I develop in the next section follows a fundamentally different approach. Technology diffusion results from choices by decentralized, heterogeneous decision makers who learn in an interactive environment not only about the performance and potential cost reductions for new technologies, but also the dynamics of other macroeconomic variables such as wages and prices.

3. Modeling the Diffusion of New Technologies through Heterogeneous Interactive Agents

The goal is to model the behavior of firms[3] in developing countries with respect to production technology choices. The reader should have in mind not exclusively "big" firms, but mostly small firms, some times family owned firms, that operate in urban or rural areas. Ghana's cocoa producers can be considered as the prototype of the agents/firms considered in the analysis. Agent's technology choices determine not only factors' productivity but also depletion rates for alternative natural resources. The focus here will be on

the "consumption" of carbon emissions (i.e., the carbon intensity of the economy).

In this model, firms or agents are characterized by their ownership of capital and their geographic location. For simplicity, I work within a one-sector economy, and I describe the model from this perspective. However, the algorithm used to solve the model is able to operate in an N-sectors economy. Of course, adding sectors increases simulation time and expands considerably the number of parameters needed to calibrate, without necessarily providing additional insights. For similar reasons, I only work with two types of technologies: an "existing" and a "revolutionary" technology characterized by higher productivity and low dependence on fossil fuels, such as Low-NOx combustion, furnace sorbent injection, or duct injection, wet and dry scrubbers (see, Tavoulareas and Charpentier, 1995 for an extensive review of the cost-effectiveness of these technologies).

It is important to stress that the focus of the model is on the process of diffusion. Several non-technology policies such as monetary, fiscal, and even trade policies, affect this process. In the case of the latter, tariffs and quotas affect the costs of new technologies that are usually imported, but also the costs of inputs that are associated with the use of these technologies. Tariffs and quotas may also protect inefficient technologies. The role of trade policy in promoting technology diffusion constitutes a research in itself. In what follows the relative costs of new technologies with respect to traditional ones will be taken as a random variable to reflect variability in the type of distortions that may exist in the market for production technologies. Yet, trade instruments will not be considered explicitly.

3.1 Choosing Among Technologies

Each technology is associated with a production function. To choose a technology, agents need to solve three interrelated problems. First, agents need to derive the supply function associated with the technology. Second,

agents need to establish where along that supply function it is optimal to produce, given expectations about prices and wages. Finally, agents need to compare inter-temporal profits under alternative technologies. The basic assumption is that these choices are undertaken to *maximize profits* and that firms have a *relatively short planning horizon*. There is no scientific support for this assumption, but it is a generally accepted phenomena in the finance/business literature, that even big firms evaluate marketing and financial strategies within relatively short horizons that range between 5 and 10 years (see Higgins, 1998). Another important assumption is that firms are *technology-costs takers*, meaning that they cannot individually influence the dynamics of technology costs.

Production Functions

To characterize the production function associated with each production technology, I use a combined Cobb-Douglas/Constant Elasticity of Substitution (CES) specification. Three types of inputs enter this production function: human capital, produced capital, and natural capital. These three aggregate factors parallel the three components of the wealth of nations (see Chapter 2) although in the case of natural resources I consider exclusively the "consumption" of carbon emissions associated with the use of fossil fuels (e.g., oil, carbon and natural gas). Hence, for an agent i using technology j at time t, the production function is given by:

$$q_{ij} = A_{jt} k_{it}^{\alpha_j} \left\{ \left[\left(\left(1 - a_j\right) \bar{l}_{it} \right)^{\rho_j} + \left(a_j n_{it} \xi_j \right)^{\rho_j} \right]^{\frac{1}{\rho_j}} \right\}^{1-\alpha_j}, \tag{5.1}$$

This apparently complicated formulation hides enormous flexibility and versatility. We observe that a Cobb-Douglas production function captures the trade-offs between produced capital (k) and non-produced capital (l and n). Hence, the elasticity of substitution between produced capital and non-produced capital is equal to one (see Nordhaus and Yohe, 1983; and Edwards, 1991, for similar functional specifications). However, in the short run, agents take the level of produced capital as given (see Section 4 for a discussion on the dynamics of the stock of capital). On the other hand, the

trade-offs between human, and natural capital, are represented by a CES production function. Hence, in the short run, agents can substitute natural capital (n) and human capital (l) with an elasticity of ρ_j<1. The other parameters of this function are as follows. The first parameter A_j, a scale factor, parallels the exogenous technological progress coefficient of the standard Cobb-Douglas function. As suggested by the time index, A_j is assumed to change over time as agents learn about the characteristics of the technologies. Hence, A_j allows us to model "learning by *using*" and will be the channel through which I formalize knowledge spillovers. The coefficient α_j is technology specific and represents the capital elasticity of output. Finally, the coefficient ξ_j captures the natural resources intensity of the technology. The higher ξ_j the lower the quantity of natural resources needed to produce a given level of output. In this case, the lower the carbon intensity of the economy. The parameter ξ_j will be one of the important uncertainties considered in this model.

Cost Functions

To derive the cost function associated with the production function (5.1), I proceed as follows. First, because capital is fixed in the short run, the cost minimization problem in terms of l and n can be written as:

$$\begin{cases} Min_{l_{it},n_{it}\xi_j} : \overline{w}_{jt}\bar{l}_{it} + z_t n_{it} \\ s.t. \\ \left((1-a_j)\bar{l}_j\right)^{\rho_j} + \left(a_j n_{it}\xi_j\right)^{\rho_j} = F^{\rho} \end{cases}, \tag{5.2}$$

where $F = \left[\dfrac{q_{ij}}{A_{jt}k_{it}^{\alpha_j}}\right]^{\frac{1}{1-\alpha_j}}$, $\overline{w}_j$ is the cost of a unit of combined, high, and low quality labor, and z is the cost of consuming one unit of natural resources with technology j. This last cost includes the costs associated with government regulations, such as permits or taxes.

The first order conditions for the minimization problem are:

$$\begin{aligned} &\overline{w}_{jt} - \lambda\rho_j\left(\left(1-a_j\right)\bar{l}_{it}\right)^{\rho_j-1}\left(1-a_j\right) = 0 \\ &z_{jt} - \lambda\rho_j\left(a_j n_{it}\xi_j\right)^{\rho_j-1} a_j = 0 \end{aligned} \quad , \tag{5.3}$$

From (5.3), we get:

$$\begin{aligned} &\left[\frac{\overline{w}_{jt}}{\lambda\rho_j\left(1-a_j\right)}\right]^{\frac{\rho_j}{\rho_j-1}} = \left(\left(1-a_j\right)\bar{l}_{it}\right)^{\rho_j} \\ &\left[\frac{z_{jt}}{\lambda\rho_j a_j}\right]^{\frac{\rho_j}{\rho_j-1}} = \left(a_j n_{it}\xi_j\right)^{\rho_j} \end{aligned} \quad , \tag{5.4}$$

By replacing (5.4) in the constraint in (5.2) we get:

$$\left(\lambda\rho_j\right)^{\frac{-\rho_j}{\rho_j-1}} = F^{\rho_j}\left\{\left[\frac{\overline{w}_{jt}}{\left(1-a_j\right)}\right]^{\frac{\rho_j}{\rho_j-1}} + \left[\frac{z_{jt}}{a_j}\right]^{\frac{\rho_j}{\rho_j-1}}\right\}^{-1} , \tag{5.5}$$

Finally by replacing (5.5) in (5.4), we get the conditional demand factor functions:

$$\begin{aligned} &\bar{l}_{it} = F\left\{\left[\frac{\overline{w}_{jt}}{\left(1-a_j\right)}\right]^{\frac{\rho_j}{\rho_j-1}} + \left[\frac{z_{jt}}{a_j}\right]^{\frac{\rho_j}{\rho_j-1}}\right\}^{\frac{-1}{\rho_j}} \overline{w}_{jt}^{\frac{1}{\rho_j-1}}\left(1-a_j\right)^{\frac{-\rho_j}{\rho_j-1}} \\ &n_{it} = \frac{F\left\{\left[\frac{\overline{w}_{jt}}{\left(1-a_j\right)}\right]^{\frac{\rho_j}{\rho_j-1}} + \left[\frac{z_{jt}}{a_j}\right]^{\frac{\rho_j}{\rho_j-1}}\right\}^{\frac{-1}{\rho_j}} z_{jt}^{\frac{1}{\rho_j-1}} a_j^{\frac{-\rho_j}{\rho_j-1}}}{\xi_j} \end{aligned} \quad , \tag{5.6}$$

System (5.6) provides the optimal demand for human capital and natural resources required to produce q_{it} units of output given factor prices. In

particular we observe that given prices, the demand for natural resources will decrease as the parameter ξ_j increases.

By placing the conditional demand functions into the objective function in (5.2), we get the cost function for technology j:

$$c_{ij}\left(\overline{w}_{jt}, z_{jt}, k_{it}, q_{it}\right) = \left[\frac{q_{ij}}{A_{jt}k_{it}^{\alpha_j}}\right]^{\frac{1}{1-\alpha_j}} \left\{\left[\frac{\overline{w}_{jt}}{\left(1-a_j\right)}\right]^{\frac{\rho_j}{\rho_j-1}} + \left[\frac{z_{jt}}{a_j}\right]^{\frac{\rho_j}{\rho_j-1}}\right\}^{\frac{\rho_j-1}{\rho_j}} \frac{1}{\varepsilon_j} + r_t k_{it}, \qquad (5.7)$$

To ease the notation, I will write:

$$c_{ij}\left(\overline{w}_t, z_t, k_{it}, q_{it}\right) = q_{ij}^{\frac{1}{1-\alpha_j}} \Gamma_{ijt} + r_t k_{it}, \qquad (5.8)$$

with $$\Gamma_{ijt} = \left[\frac{1}{A_{jt}k_{it}^{\alpha_j}}\right]^{\frac{1}{1-\alpha_j}} \left\{\left[\frac{\overline{w}_{jt}}{\left(1-a_j\right)}\right]^{\frac{\rho_j}{\rho_j-1}} + \left[\frac{z_{jt}}{a_j}\right]^{\frac{\rho_j}{\rho_j-1}}\right\}^{\frac{\rho_j-1}{\rho_j}} \frac{1}{\varepsilon_j}.$$

Profit Functions

Given our level of aggregation, it is reasonable to assume that agents act competitively within their economic sectors. Hence, they maximize profits by setting marginal costs equal to the market price. Under this assumption, maximum profits using technology j are given by:

$$\pi_{ijt}^{*} = \left[\frac{p_{gt}^{*}\left(1-\alpha_j\right)}{\Gamma_{ijt}}\right]^{\frac{1-\alpha_j}{\alpha_j}} p_{gt}^{*} - \left[\frac{p_{gt}^{*}\left(1-\alpha_j\right)}{\Gamma_{ijt}}\right]^{\frac{1}{\alpha_j}} \Gamma_{ijt} - r_t k_{it}, \qquad (5.9)$$

where p_{gt}^{*} is the equilibrium price in sector g.

We notice that the profit function defined by (5.9) is based on an *equilibrium price* that is unknown at the time producers undertake their technology

decisions. This implies that technology choices depend on agents' *expectations* about this clearing price. Further, agents do not have perfect information about the cost of human and natural capital embedded in Γ_{ijt}, or about the opportunity cost of capital r_t (although, because we assume that the latter is the same for all technologies, it will drop out of the choice problem). For now, I will assume that each agent has well-defined expectations about each of the components of the profit function (i.e., the agents know the mean vector of these random variables, as well as their variance covariance matrix), and therefore are able to compute for each technology the mean profit $E[\pi_{ijt}]$ and its variance $V[\pi_{ijt}]$. Sub-section 3.4 shows how these calculations take place.

Choices: Should I Stay or Should I Go

Within a dynamic framework, agents need not only to decide whether to switch to a new technology, but also *when* to switch to that technology. Jaffe and Stavins (1994 and 1995) analyze this issue in the context of pollution regulation. They ask when is the optimal time to switch from a high polluting technology to a low polluting technology, given pollution taxes, technology subsidies, or quotas. My framework differs from Jaffe and Stavins in that they do not consider uncertainty.

An agent using the "existing" technology needs to compare the present value of expected profits to the present value of expected profits of the new technology. Therefore, I assume that at the end of period t, each agent first needs to evaluate whether switching to the new technology at the beginning of period t+1 is profitable. Further, I assume that profits are received at the end of each time period. Under these assumptions the *profitability condition* implies:

$$\sum_{k=t+1}^{T} E[\pi_{ij'k}]\theta^{k-t} - \Lambda_{ij't} \geq \sum_{k=t+1}^{T} E[\pi_{ijk}]\theta^{k-t}, \qquad (5.10)$$

where $\Lambda_{ij't}$ is a fixed cost associated with the adoption of technology j' (for a similar specification, see Durlauf, 1993). The profitability condition can be rewritten as:

$$\Lambda_{ij't} \leq \sum_{k=t+1}^{T} \left\{ E\left[\pi_{ij'k}\right] - E\left[\pi_{ijk}\right] \right\} \theta^{k-t}, \tag{5.11}$$

which states that switching is profitable if the cost of adoption is lower than the present value of the expect gains of adoption.

If condition (5.11) holds, then the agent needs to assess whether waiting to adopt will be even more profitable. Indeed, an agent may expect, for example, that the adoption cost will be lower in the future. Formally, waiting to adopt the technology at the beginning of time t+1 will be optimal if the following condition, the *arbitrage condition*, holds:

$$E\left[\pi_{ijt+1}\right]\theta + \sum_{k=t+2}^{T} E\left[\pi_{ij'k}\right]\theta^{k-t} - E\left[\Lambda_{ij't+1}\right]\theta \geq \sum_{k=t+1}^{T} E\left[\pi_{ij'k}\right]\theta^{k-t} - \Lambda_{ij't}, \tag{5.12}$$

This condition states that it is optimal to wait if the net profits of switching tomorrow while facing a switching cost $E\left[\Lambda_{ij't+1}\right]$ are higher than the profits received by switching today with a cost $\Lambda_{ij't}$. Notice that $\sum_{k=t+1}^{T} E\left[\pi_{ij'k}\right]\theta^{k-t}$ in (5.12) can be rewritten as $E\left[\pi_{ij't+1}\right]\theta + \sum_{k=t+2}^{T} E\left[\pi_{ij'k}\right]\theta^{k-t}$. Therefore condition (5.12) can be rewritten as:

$$\Lambda_{ij't} - E\left[\Lambda_{ij't+1}\right]\theta \geq \left\{ E\left[\pi_{ij't+1}\right] - E\left[\pi_{ijt+1}\right] \right\}\theta, \tag{5.13}$$

This condition states that it is optimal to wait if the expected gains from waiting (the first part of the inequality) are greater than expected costs of waiting (the forgone profit given by the second part of the inequality).

In summary, an agent should switch to the new technology at time t only if:

$$X_p \geq 0 \quad \text{and} \quad X_a \geq 0, \tag{5.14}$$

where $X_p = \sum_{k=t+1}^{T} \left\{ E\left[\pi_{ij'k}\right] - E\left[\pi_{ijk}\right] \right\} \theta^{k-t} - \Lambda_{ij't}$ and $X_a = \left\{ E\left[\pi_{ij't+1}\right] - E\left[\pi_{ijt+1}\right] + E\left[\Lambda_{ij't+1}\right] \right\} \theta - \Lambda_{ij't}$

I will show in Sub-section 3.4 that all the expectations in (5.14) are asymptotically normally distributed given a range of values for the support of the expectations. This being the case, X_p and X_a are normally distributed as well. I add the assumption that X_p and X_a are independent. Therefore, agents can compute:

$$\phi_{jj'} = \Pr\left[X_p \geq 0\right] \Pr\left[X_a \geq 0\right], \tag{5.15}$$

which is the probability that the decision of switching will be correct.

My final assumption is that agents will switch to the new technology on the basis of their "reservation level" $0 \leq \lambda_i \leq 1$, which depends on their risk aversion. Hence, an agent i at time t will switch from technology j to technology j' if:

$$\phi_{jj'} \geq \lambda_i + \varepsilon, \tag{5.16}$$

where ε is white noise. This noise is introduced to take into account that agents do not always do the right thing, or that their decisions are influenced by factors not taken into account by our models (see Young, 1998; and Radner, 1996).

It is trivial to show that, given a vector of prices, the probability $\phi_{jj'}$ increases with the "size" of the agent (i.e., its ownership of capital). Indeed, from (5.11) we see that the derivative of expected profits with respect to the gamma function is negative. We also observe from the definition of the gamma function, that its derivative with respect to the level of produced capital is negative. Thus, other things being equal, expected profits will increase with the level of produced capital. The implication, is that, other things being equal, agents with a higher endowment

of produced capital will be more likely to switch to a new technology than agents with lower endowments, due to economies of scale. Thus, the model reproduces a well-known finding in the literature on technology diffusion (see Sahal, 1981). The idea is illustrated in Figure 5.2. The figure was constructed by simulating technology choices for a sample of 100 agents, using mean values for the model parameters (see Section 5).

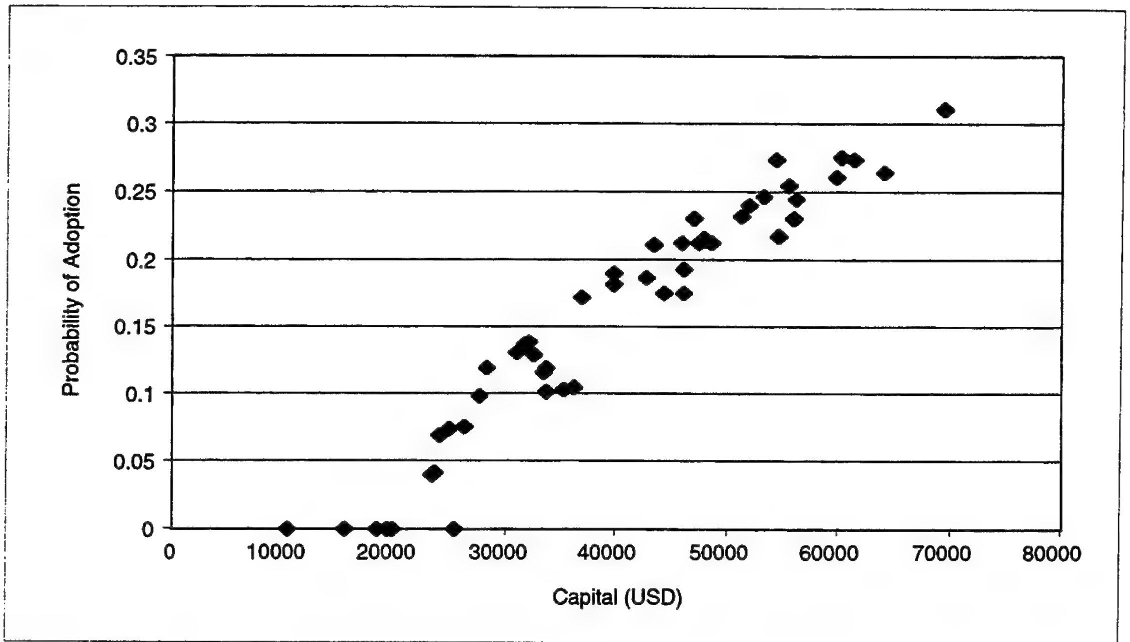

Figure 5.1: Capital Ownership and Probability of Adoption.

3.2 Social Interactions and Cooperative Behavior

Up to this point, I have been assuming that choices are made given expectations, independently of the choices of other agents. Yet, Chapter 3 provided several reasons why cooperative behavior is an important factor influencing technology choices. In this sub-section, I will focus on the effects of cooperation on adoption costs. Our example of the farmer in the Andes Mountains falls into this category. In general, if the adoption decision is undertaken simultaneously by a community of potential users, adoption costs tend to be lower due to economies of scale, or because as a group adopters may have access to better prices.

To formalize this phenomenon, I recall the definitions of networks from Chapter 3. I assume that agents/firms in a given developing economy operate in a graph G(V,E). The two dimensions of the space V may be given economic interpretations. The first dimension (K) can be viewed as a one-dimensional social space. Agents' location in this space depends on their ownership of capital. The second dimension (C) is simply a one-dimensional geographic space. Agents are randomly located in this dimension. Hence, a vertex of the graph is a vector $i=(k_i,c_i);\ k_i \in K,\ c_i \in C,\ V = K \times C$ that characterizes an agent in terms of its ownership of capital and its location in the geographical space. As usual, I define the neighborhood of agent i by the set of other agents with whom agent i shares an edge (i.e., has a connection), $v(i)=\left\{j \in V; \{i,j\} \in E,\ i \neq j\right\}$. As suggested in Chapter 3, networks can be, in part, characterized by the statistical process that governs the emergence of connections. To define this statistical process, I assume that the probability that two agents establish a connection is related to their distance in social and geographic space. For example, in Ecuador, small producers of corn are more likely to interact with other small producers of corn, and less likely to interact with producers of bananas, which are usually owners of large plantations. Similarly, corn producers from the Andes region are less likely to interact with corn producers from the coast. Formally, the probability that agent i and agent i' will be connected is given by:

$$\Pr(i \leftrightarrow i') = \frac{1}{1+\exp\left[-\left(2-\frac{2}{\beta_1 Var(k)^2}(k_i-k_{i'})^2+\frac{2}{\beta_1 Var(c)^2}(c_i-c_{i'})^2\right)\right]}, \tag{5.17}$$

where β_1 is a connectivity parameter. As this parameter increases, the probability of connection also increases. Two examples of networks with 100 agents, constructed with $\beta_1 = 0.1$ and $\beta_1 = 0.5$ are given in Figure 5.2.

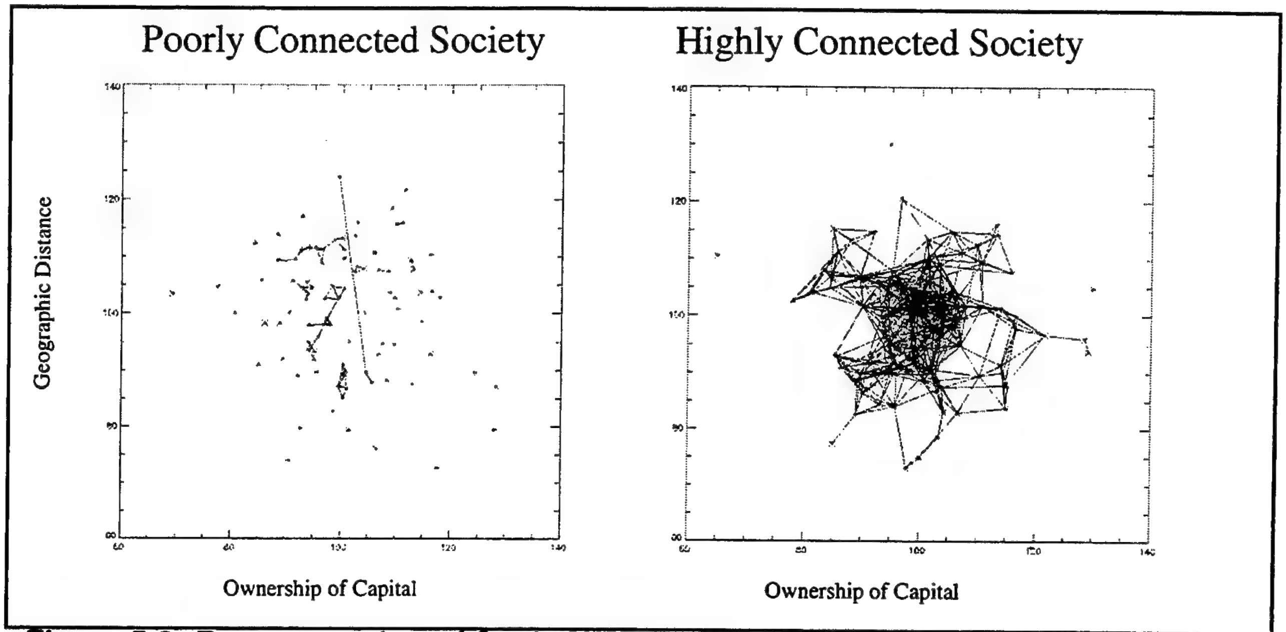

Figure 5.2: Representation of Social Networks.

We observe that the average number of connections per capita increases as the connectivity parameter increases. For example, in the network $\beta_1 = 0.1$, agents have on average a single connection. At the extreme, in the network $\beta_2 = 0.5$, each agent is on average connected to 6 other agents (see Figure 5.3)[4].

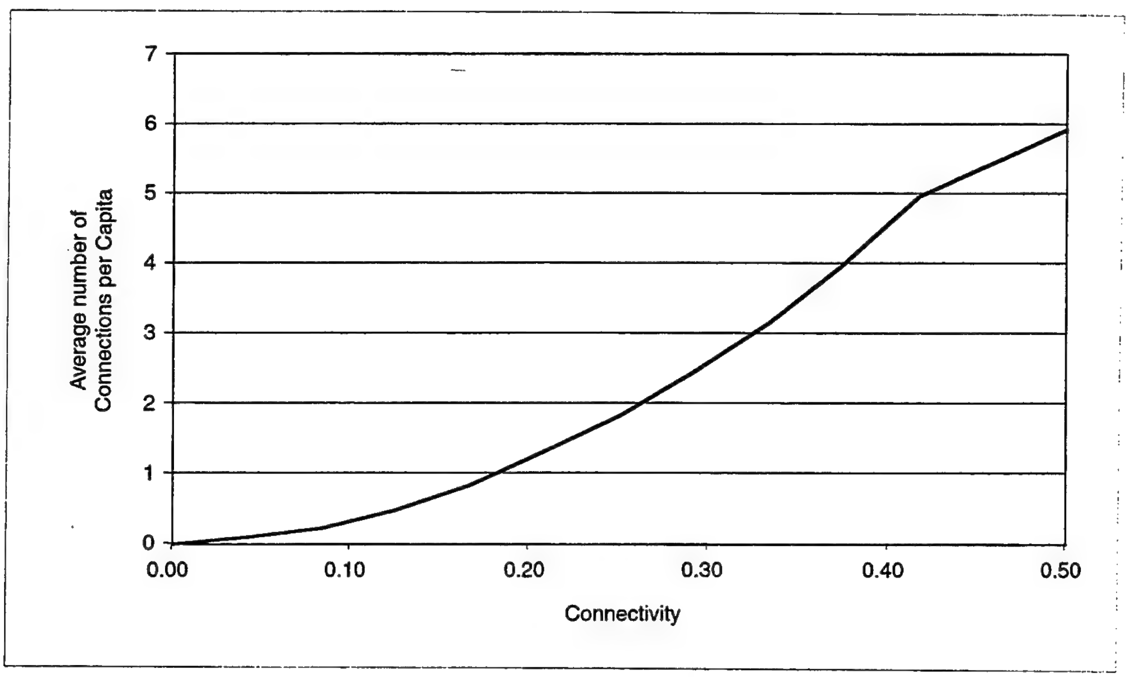

Figure 5.3: Connectivity and Connections Per Capita.

The network is also characterized by the prevalence of cooperative behavior among the members of the network. Therefore, with some probability χ - that is an intrinsic characteristic of the country under analysis - cooperative behavior between an agent and its neighbors can emerge[5]. In summary, the network class is characterized by the vector (β_1, χ).

What happens when cooperative behavior emerges? As discussed in Chapter 3, the main implication of cooperative behavior is that when adoption of a new technology is undertaken simultaneously by a group of agents, costs may be lower than those faced by a single agent. To formalize this idea, I assume that the cost of adoption for the group decreases with the number of agents in the groups. This idea can be formalized through the popular logistic form:

$$\Lambda_{v(i)t} = \Lambda_t |v(i)|^{-\beta_2}, \tag{5.18}$$

where as before Λ is the cost of adoption, v(i) is the set of neighbors of agent i, $|\ |$ represents "the number of elements" in the set, and β_2 is a parameter that captures the level of social spillovers, or the percentage of decrease in the adoption cost that results from a one percent increase in the number of members in agent i's neighborhood.

With cooperative behavior, agents analyze jointly the profitability and arbitrage conditions. In other words, they do not focus on an individual's expected profits, but rather add individual costs and benefits to come up with costs and benefits for the group. By definition, under cooperative behavior, costs are lower for everybody. However, it may be the case that for some agents the adoption of the new technology is still not profitable. Yet, "winners" can compensate "losers" in exchange for the marginal contribution to the reduction in adoption costs.

Similarly to the individual case, the condition for adoption by members of a group, composed by agent i and its neighbors, is given by:

$$\phi_{v(i)jj'} > \lambda_{v(i)}, \tag{5.19}$$

where $\phi_{v(i)jj'} = \Pr\left[X_{v(i)p} \geq 0\right]\Pr\left[X_{v(i)a} \geq 0\right]$, $\lambda_{v(i)} = \frac{1}{|v(i)+1|}\sum_l \lambda_l;\ l \in v(i)$,

$$X_{v(i)p} = \sum_l \left\{ \sum_{k=t+1}^{T} \left\{ E_{v(i)}\left[\pi_{lj'k}\right] - E\left[\pi_{ljk}\right] \right\} \theta^{k-t} - \Lambda_{v(i)j't} \right\};\ l \in v(i) \text{ and}$$

$$X_{v(i)a} = \sum_l \left\{ \left(E_{v(i)}\left[\pi_{ij't+1}\right] - E\left[\pi_{ijt+1}\right] + E_{v(i)}\left[\Lambda_{ij't+1}\right] \right)\theta - \Lambda_{v(i)j't} \right\};\ l \in v(i)$$

In the last three expressions, i indexes the agent who is analyzed, l indexes the members of the group, and j indexes technologies. We observe that expectations about profits by each agent l, are indexed by ν(i). This is due to the fact that agents compute expected costs and benefits on the basis of social expectations about prices, wages, and the cost of natural resources. In other words, they take into account not their individual expectations of prices and wages, and the cost of natural resources, but rather the average of the expectations of all members of i's neighborhood. We also observe that the coefficient of risk aversion is the average of individual risk aversion coefficients.

3.3 Social Interactions and Knowledge Spillovers

In my discussion on social capital (Chapter 3), I showed that one of the main channels through which social networks affect the dynamics of the economy are knowledge spillovers. In the case of Africa, for example, Collier and Gunning (1999) suggested that low levels of knowledge spillovers explain in part poor economic performance. Also, in the case of the diffusion of hybrid cocoa in Ghana, social networks were important sources of "knowledge". This process can be viewed as a "learning by using" process - a demand characteristic of the technology. "Learning by using" differs from the more popular "learning by doing" process, a supply characteristic of the technology, that refers to the well-known phenomena that during the process of technology diffusion, adoption costs tend to decrease as the number of users increase (see Sub-section 4.5 for a discussion of this process and its effects on the dynamics of Λ_j).

Learning by doing refers to the process by which economic agents discover more efficient ways of using a given technology. It also refers to the process by which agents, in their social interactions, gain information about the performance of alternative production technologies and improvements to their *modus operandi*. In research, for example, we constantly learn from our colleagues about new theories, new ideas and statistical tools, or simply new computer programs. What in research appears to be pervasive, is pervasive in other activities as well. Physicians learn about new medicines and medical interventions from their peers; and farmers learn about new seeds or fertilizers from other farmers in their community. As I mentioned earlier, I formalize this idea through the technology factor A_{ijt}.

At the beginning of each simulation, this factor is the same across all agents, and varies only across technologies. As agents gain experience with the technology, they discover ways of making things work more efficiently, and Aij increases. These improvements, that are independent from the actions of other agents, are assumed to occur by chance. That is, there exists a probability distribution governing the arrival of improvements. I assume the arrival distribution is Poisson. Hence, for agent i *using* technology j, the dynamics of A_{ijt}, in the absence of interactions, is given by:

$$\begin{cases} \overline{A_{ijt}} = A_{ijt-1}(1+\psi_0); \; \textit{with} \;\; \textit{probability} \;\; \dfrac{e^{-\psi_1}\psi_1^t}{t!} \\ A_{ijt} = A_{ijt}; \; \textit{with} \;\; \textit{probability} \;\; 1-\dfrac{e^{-\psi_1}\psi_1^t}{t!} \end{cases}; \qquad (5.20)$$

This implies that at any time t, an innovation/improvement by agent i can be observed with a probability given by the first expression in (5.20). This improvement will increase A_{ijt} by $\psi_0/100$ percent. Thus, innovations are governed by the two parameters: ψ_0, the marginal innovation rate, and ψ_1, the mean arrival rate. We notice that because the arrival of improvements is Poisson distributed, the probability of observing these improvements decreases with time. This is a standard assumption when modeling productivity growth (see for example Pizer, 1998). It captures the well-known phenomena that

innovations to a given technology accelerate during the fist stages of the diffusion process, and decay afterwards (see Sahal, 1981).

I mentioned that learning by using also involves learning about the innovations of other agents, or more precisely, about their *techniques*. Hence, when agent i and agent l interact, they compare their techniques. If the technique of one of them, say l, is better than that of the other (i.e., the A factor is greater), the agent with the least efficient technique will learn from the agent with the most efficient technique (in this case l). Learning involves increasing factor A_{ijt} by a given fraction of the difference in levels of efficiency $\left(A_{ljt} - A_{ijt}\right)$. We have:

$$\begin{cases} A_{ijt} = A_{ijt} + \psi_2\left(A_{ljt} - A_{ijt}\right); \; l \in v(i) \;\; if \;\; A_{ljt} > A_{ijt} \\ A_{ijt} = A_{ijt}; \; otherwise \end{cases}; \qquad (5.21)$$

The "quantity" of learning from the interaction is therefore regulated by the parameter ψ_2. This parameter becomes a proxy for the "quality" of network connections. Presumably, as the level of education of a given population of agents increases, ψ_2 should increase as well.

The dynamics of A_{ijt} will affect the process of technology diffusion as well as the growth rate of the economy. Its dynamics will in turn be related to the density of connections in the network. To illustrate this idea, I have performed the following computational experiment. For different network classes, I have computed the average share of the population (average taken over 100 Monte Carlo simulations) that after a fixed period of time (set arbitrarily to 5 years) know about a given innovation that occurred at time 0 (i.e., agents who have increased their original A in proportion to the size of the innovation). The results of this experiment are summarized in Figure 5.4. It is clear that the "speed" at which information diffuses through the network depends on the level of connectivity. Higher connectivity leads to a higher share of the population being aware of the invention. However, higher connectivity will not necessarily be associated with a faster diffusion of new

technologies. Indeed, information flows are not reserved to "revolutionary" technologies. Hence, higher connectivity may favor old technologies intensive in natural resources, and act as a limiting factor for economic growth (see Sub-section 5.3).

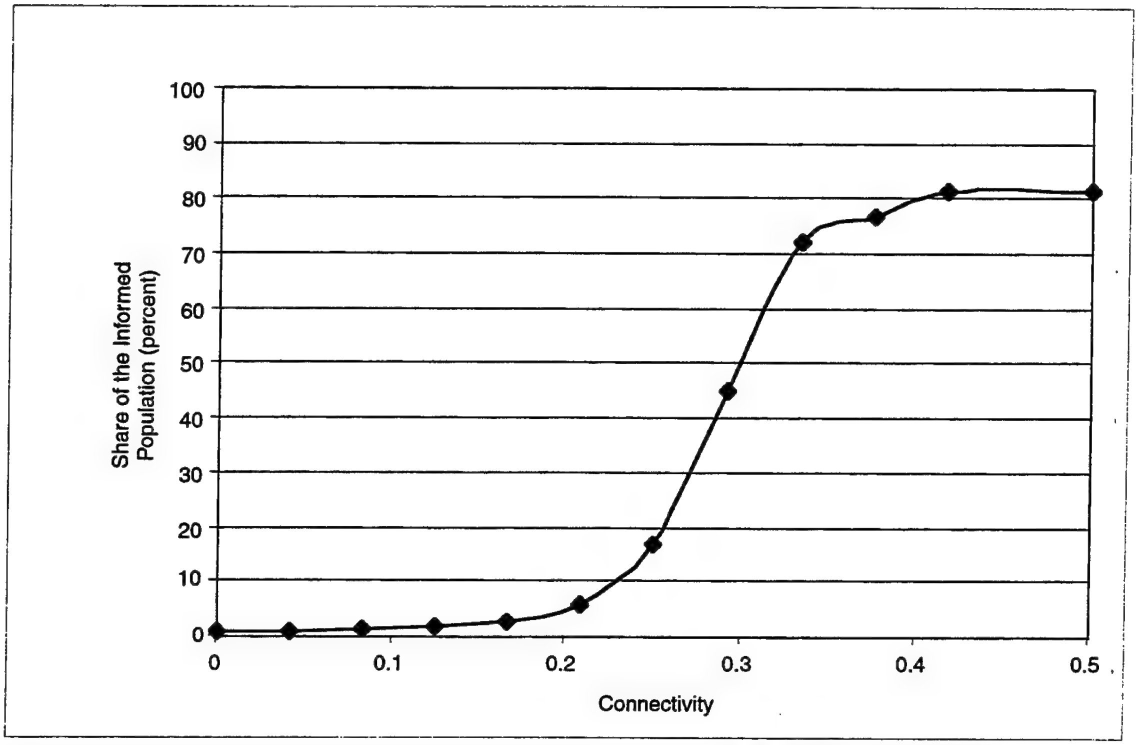

Figure 5.4: Effect of Network Connectivity on Knowledge Diffusion.

In summary, the effect that networks have on the diffusion of new technologies and productivity growth is captured by the vector of parameters $(\beta_1, \chi, \beta_2, \psi_0, \psi_1, \psi_2)$, respectively the degree of connectivity, the probability of emergence of cooperative behavior, the degree of social spillovers, the marginal innovation rate, the average rate of innovation, and the quality of network connections. These six parameters determine what I have called a *network class* (see Chapter 3).

3.4 Generating Expectations about the Dynamics of the Economy

Agents in this model need to generate expectations about four macroeconomic variables: output prices, cost of labor, cost of natural resources including

environmental regulations, and cost of new technologies. The dynamics of these variables can be approximated by a function of the form:

$$y_t = y_0 t^{b_y}, \tag{5.22}$$

Hence, depending on the value of b, time series can grow exponentially (b>1), decrease exponentially (b<-1), converge to a plateau from below (0<b<1), or converge to plateau from above (1<b<0).

For any time series of interest $\{y\}_t$, agents are assumed to act as econometricians and generate estimates of b_y on the basis of observed trends. Equation (5.22) implies:

$$y_t = y_{t-1}\left(\frac{t}{t-1}\right)^{b_y};\ t>1, \tag{5.23}$$

Therefore, agents estimate the model:

$$\log\left(\frac{y_t}{y_{t-1}}\right) = b_y \log\left(\frac{t}{t-1}\right), \tag{5.24}$$

The general estimation method that agents use is Recursive Least Squares (see Sargent, 1992). Hence, if we call z the endogenous variable and **x** the vector of exogenous variables (possibly including a vector of ones), the expected value of the vector of coefficients β_t in the model $z_t = \mathbf{x}_t\beta_t$ is given by: $\beta_{t+1} = \beta_t + RR\left(\Omega_t^{-1}\mathbf{x}_t\right)\left(\beta_t^{obs} - \beta_t\right)$ while the variance is given by $\Omega_{t+1} = \Omega_t + RR\left(\mathbf{x}_t'\mathbf{x}_t - \Omega_t\right)$ where RR is an exogenously defined adjustment factor that determines the speed of convergence, and β_t^{obs} is the *observation* of the parameter β, at time t. In this case of model (5.24), this observation will be generated by dividing $\log\left(\frac{y_t}{y_{t-1}}\right)$ by $\log\left(\frac{t}{t-1}\right)$.

This specification of the learning model supports a wide variety of formulations for the model driving the dynamics of the macroeconomic variables of interest. For our application, the formulation used in (5.24) is sufficient.

For a time series $\{y\}_t$, given agents' estimator of b_y, they can generate forecasts with mean and variances approximated by[6]:

$$\begin{aligned} E[y_{t+k}] &= y_t\left(\frac{t+k}{t}\right)^{E[b_y]} \\ V[y_{t+k}] &= V[b_y]\left[y_t\left(\frac{t+k}{t}\right)^{E[b_y]}\log E[b_y]\right]^2, \end{aligned} \tag{5.25}$$

In order to choose among technologies agents must have an estimate of future profits. In particular, the profit function requires expectations about the price of output, the cost of labor and the cost of natural resources. Agents use (5.25) to generate expectations about these variables. Given these expectations the process to estimate expected profits and their variance is a little more cumbersome. Indeed, given that the profit function is a non-linear function of random variables, the agents need to use the theorem for the *Asymptotic Distribution of Non-Linear Functions* (see Green, 1997):

Call $\hat{\theta}$ *the vector of estimates E[y] of the random variables y included in the profit function* $\pi(\theta)$, *such that* $\hat{\theta}\xrightarrow{a}N[\theta,(1/n)V]$ *where V is the variance covariance matrix; then* $\pi(\hat{\theta})\xrightarrow{a}N[\pi(\theta),(1/n)\Pi(\theta)\mathbf{V}\Pi(\theta)']$, *where* $\Pi(\theta)=[\partial\pi/\partial\theta_1 \quad \ldots \quad \partial\pi/\partial\theta_k]$ *is a row vector of partial derivatives of the profit function with respect to each of the random variables.*

Once $\Pi(\theta)$ has been computed, it is straightforward to compute expected profits and their variance. Notice, however, that this is a way to compute profits at the expected values of the random variables. Given that the profit function is convex (see Varian, 1992) this value is lower than the true expected profit (the mean of profits integrating along the different random variables). This bias however applies to all the technologies. Since we are interested in choosing across technologies, we will assume this bias largely

cancels out. That is, we allow choices to be based on profits computed at the mean value of the random variables.

3.5 Outputs from the Model of Technology Diffusion

Before moving to the description of the macro-econometric model (Section 4), I summarize in this sub-section the outputs that can be derived from the model of technology diffusion (see Sub-sections 3.1 to 3.4).

Production and the demand for labor and carbon emissions

Given his/her choice of technology and expectations about prices, wages, and the cost of natural resources, agent i computes the optimal level of output, q_{it}, to be produced at time t. This level of output is given by the first bracket in the profit function (equation 5.9). Agent i also computes the optimal demand for labor, $\bar{l}_{it}$, and carbon emissions, n_{it}, given by equation (5.6). Therefore, from the model of technology diffusion, by adding across agents we derive the aggregate output, Q, and the aggregate demand for labor, l, and carbon emissions, n,. We have:

$$Q_t = \left(\sum_i q_{it}\right)\left(1 - d_0\left(\frac{n_t}{n_0}\right)^{d_1}\right), \tag{5.26}$$

$$n_t = \sum_i n_{it}, \tag{5.27}$$

$$\text{and} \quad \bar{l}_{ht} = \sum_i \bar{l}_{hit}. \tag{5.28}$$

We notice that total output is affected by the damages resulting from environmental degradation. In this case these damages are given by the quantity of carbon emissions at time t, n_t, the initial level of carbon emissions, n_0, and unknown parameters d_0 and d_1.

Aggregates computed in equations (5.26-5.28) will be passed to the macro-econometric model that will in turn compute changes in prices, changes in the stock of capital, environmental damages, and other macroeconomic aggregates. The model is described in the next section.

4. The Macro-econometric Model

For analytical purposes, the model of technology diffusion is coupled to the macroeconometric model for the developing world developed in Huaque et al. (1993). This model implements policies and computes output prices, wages, the savings rate of the economy[7], the costs of natural resources and new technologies, changes in the stock of natural and produced capital, as well as environmental damages.

4.1 Basic Identities

The core of the macro model is presented in Table 5.1. Most of its structure and parameters will be taken as given, so my discussion of the table will be limited. Huaque et al. (1993) offers a more detailed description of the model.

The functions in the table are respectively the aggregate production of the economy (A1), the consumption function (A2), the investment function (A3), the exports function (A4), the imports function (A5), the real money demand (A6), the equation determining the nominal interest rate (A7) and the monetary/external (A8) and income/expenditures identities (A9). The parameters of the model have been estimated in Huaque et al. (1993).

The production function A1, has been replaced by the production function (5.26) in the model of technology diffusion. For the other functions, A2 to A7, the specification is standard. Real consumption (A2) is assumed to be a function of disposable income (Yd), the real interest rate (r) and lagged values. Investment (A3) is defined as a function of the interest rate, aggregate output (Y), and lagged values. Exports (A4) and imports (A5) respond to changes in the real exchange rate (rer), aggregate output (Y), as well as lagged values. In the case of imports, the availability of

international monetary reserves (IMR) also has an effect. Equation (A6) is the real money demand function, assumed to depend on the level of aggregate activity (Y) and the nominal interest rate (i). Finally, the domestic nominal interest rate depends on the degree of capital mobility, captured by the parameter ϕ. When ϕ equals 0 (the case with no mobility), the domestic nominal interest rate equals the shadow interest rate (the interest that would prevail in the absence of capital flows from the rest of the world). When ϕ equals one (perfect mobility), the domestic nominal interest rate is determined by the international interest rate and the expected devaluation of the nominal interest rate (ner) of the economy. Identity (A8) states that the supply of money is given by the level of the international monetary reserves (IMR) and the domestic credit (DC).

$$A1)\quad Y_t = K_t^{0.12} L_t^{0.88} e^{0.14t}$$

$$A2)\quad \log C_t = cte - 0.076 r_t + 1.010 \log C_{t-1} + 0.143 \log Yd_t - 0.149 \log Yd_{t-1}$$

$$A3)\quad I_t = cte - 0.113(r_t - r_{t-1}) + 0.196(Y_t - Y_{t-1}) + 0.809 I_{t-1}$$

$$A4)\quad \log X_t = cte + 0.0495 \log rer_t + 0.084 \log Y_t^* + 0.925 \log X_{t-1}$$

$$A5)\quad \log Z_t = cte - 0.157 rer_t + 0.161 \log Y_t + 0.038 \log \frac{IMR_{t-1}}{P_t^* Z_{t-1}} + 0.834 \log Z_{t-1}$$

$$A6)\quad \log \frac{M_t}{p_t} = -0.146 - 0.038 i_t + 0.571 \log Y_t - 0.397 \log Y_{t-1} + 0.881 \log \frac{M_{t-1}}{p_{t-1}}$$

$$A7)\quad i_t = \phi\left(i_t^* + \frac{E_t ner_{t+1} - ner_t}{ner_t} \right) + (1-\phi)\bar{i}_t; \quad \phi = 0.91$$

$$A8)\quad M_t = ner_t IMR_t + DC_t$$

$$A9)\quad Y_t = C_t + G_t + I_t + X_t - Z_t$$

Table 5.1: Macroeconometric Model for the Developing World.

Source: Huaque et al. (1993).

Finally, (A9) states that real gross domestic product identically equals domestic absorption (C+I+G) plus the current account balance (X-Z). The parameter *cte* in all equations refers to a constant that is computed to calibrate the model to initial conditions.

4.2 Dynamics of the Stock of Produced and Natural Capital

The stock of produced capital follows the discrete formulation:

$$K_t = K_{t-1}(1-\delta_k) + I_{t-1}, \tag{5.29}$$

where δ is the depreciation rate.

Similarly, the dynamics of the stock of natural resources is given by:

$$N_t = N_{t-1}(1+R) - n_{t-1}, \tag{5.30}$$

where R is the replenishment rate and n is the quantity of natural resources consumed. However, given that our concern is with the dynamics of carbon emissions, in this application, the stock of the natural resources under consideration (fossil fuels) will play no role in our discussions.

4.3 Dynamics of Wages

To model the labor market, I have adopted a disequilibrium approach (see Muet, 1993). The fundamental reason is that in most developing countries, the labor market is not competitive and wages do not tend to adjust "inmediatly". For instance, there is extensive evidence of nominal wage downward-rigidity (see Akerloff et al., 1996 for a review). I make two simplifying assumptions. First, the supply of total labor force, L, is given by the growth rate of the population. We have:

$$L_t = L_0(1+\varphi)^t, \tag{5.31}$$

Second, given the demand for labor (equation 5.28), the dynamics of wages is characterized by:

$$w_{lt+1} = w_{lt}\left[1-\omega\left(\frac{L_t}{\bar{l}_t}-1\right)\right], \tag{5.32}$$

where ω is a parameter used to capture the degree of "stickiness" in the labor market, or alternatively, the speed of adjustment.

4.4 Dynamics of the Cost of Fossil Fuels

The market for natural resources is forced to clear in each time period. While in practice the markets of fossil fuels have been heavily regulated, mostly subsidized during the seventies and eighties, this assumption is made given that in this analysis we are taking a normative approach. Hence, we are interested in determining the optimal "consumption" of carbon emissions over time. This optimal consumption implies some dynamics for the price, that then can be compared to observed dynamics. Therefore, the supply of natural resources, n_t, is treated as a policy variable, and the price of natural resources, z, is adjusted to ensure that the demand resulting from equation (5.27) is equal to the targeted supply. Implicitly, the level of n_t can be associated with the level of permits for the consumption of carbon that the government is willing to distribute.

There is an important caveat. To estimate model parameters, we cannot treat n_t as a policy variable. Indeed, we are interested in reproducing observed dynamics of the oil and carbon intensities of developing economies (see next section). This implies that n_t needs to be treated as an endogenous variable. This also implies, however, that we need to determine somehow the dynamics of the observed price for oil and carbon. While we do observe this price at the international level (see Table 5.2), we do not have time series on a country by country basis.

In fact, while at the international level the prices of both oil and carbon have been falling during the last two decades, at the national level the prices have been increasing as subsidies have been eliminated (see Appendix 8.6 for country specific oil, gas and carbon intensities). Furthermore, different countries have implemented different types of regulatory policies for the price of oil and carbon.

Years	1980	1985	1990	1991	1992	1993	1994	1995	1996	1997	1998
Petroleum	224.0	173.0	100.0	83.0	78.0	69.0	63.0	63.0	78.0	77.0	55.0
Coal, Australian ($/mt)	55.9	49.2	39.7	38.8	36.2	29.5	29.3	33.0	33.4	32.4	28.1
Coal, US ($/mt)	59.9	67.9	41.7	40.6	38.1	35.7	33.1	32.9	32.6	33.6	33.1
Natural gas, Europe ($/mmbtu)	4.7	5.4	2.6	3.0	2.4	2.5	2.2	2.3	2.5	2.5	2.3
Natural gas, US ($/mmbtu)	2.2	3.6	1.7	1.5	1.7	2.0	1.7	1.4	2.4	2.3	2.0
Petroleum ($/bbl)	51.2	39.6	22.9	19.0	17.8	15.8	14.4	14.4	17.9	17.7	12.6

Table 5.2: Prices of Oil, Gas, and Carbon.

As a consequence, I have defined a general function for the dynamics of prices, which parameters need also to be estimated. Basically, I will ask the question of what type of price dynamics are consistent with observed depletion rates for fossil fuels. The function that is used to be able to reproduce a wide class of dynamics across the developing world is given by:

$$\log Pn_t = \log Pn_{t-1} + (\gamma_1 - 1)t + \gamma_2 u_t \qquad u \sim N(0,1), \tag{5.33}$$

This specification follows Nelson and Plosser (1982), and states that the price of fossil fuels follows a random walk with a drift that can be positive or negative. Other things being equal, countries where the price of fossil fuels has been increasing are more likely to reduce the consumption of fossil fuels. However, it is not impossible that countries where prices for fossil fuels have been decreasing also reduce their consumption given important innovations in production technologies that do not require fossil fuels as inputs. I emphasize that function (5.33) is only used for estimation purposes. It will not have any role when the model is used from a prescriptive point of view.

4.5 Dynamics of the Cost of New Production Technologies

There is extensive evidence that the production and distribution costs of new technologies decrease with the aggregate number of users (see Grübler, 1998 for a review). Developing countries are usually price takers in the world technology market. Hence, reductions in technology prices result mostly from

investments that take place *outside* the developing country under analysis. Therefore, there is a component in the cost function for the new technology that is not linked to domestic demand for that technology. Given these considerations, I postulate that the cost of the new technology for a *single* agent is given by:

$$\Lambda_t = \exp\left(\Lambda_0 - b_1 \log D_t - b_2 t + \mu\right)\left(1 - S_t\right), \tag{5.34}$$

where Λ_0 is the cost of the "first unit", D is the number of domestic users of the technology, t is time, and $\mu \sim N(0,\sigma_u)$ is white noise. The last two terms of (5.34) are meant to capture changes in prices that result from exogenous factors. The variable S_t is a policy variable that gives the level of the technology subsidy that the government implements. In summary, the cost of a new technology for a given agent is affected by three factors: world demand for the technology, *aggregate domestic* demand, and as discussed earlier, *local domestic* demand (i.e., reduction in costs resulting from coordinated actions with his/her neighbors: see equation 5.18).

4.6 Policy Variables and Aggregate Savings

The vector of policy instruments is given by: I_t, n_t, S_t that represent respectively, investments in produced capital, consumption of natural resources, and technology subsidies. As discussed in Chapter 4, these instruments should be employed to maximize intertemporal social welfare, measured by the utility function:

$$U(C_t) = L_t \frac{\left(C_t / L_t\right)^{1-\tau}}{1-\tau}, \tag{5.35}$$

The policy instruments also need to satisfy the following constraints:

$$\begin{cases} Y_t - C_t - (X_t - Z_t) - g = I_t + S_t \\ n_t \leq N_t \end{cases}, \tag{5.36}$$

where g are government net savings excluding investments in produced capital (i.e., g includes tax net of wages and interest payments). For simplicity, I will assume that X and Z result from an exchange rate policy that keeps the real exchange rate constant. I also assume that monetary policy is implemented in order to target 0 inflation). Therefore, given the dynamics of X-Z (the current account deficit) and assuming a fixed g, I will look for: i) the share s* of $Y_t - (X_t - M_t) - g$ that should be saved; ii) the optimal allocation of these savings between I and S; and iii) the optimal consumption of carbon emissions n_t. This optimization problem is described in detail in the next chapter. I do not make any assumptions regarding the ability of markets or governments to generate optimal schedules for savings, investments, and the consumption of carbon. Rather, I am taking a normative approach, and estimating directly these optimal schedules. Eventually, these could be compared to observed macro aggregates as a mean to evaluate the performance of a given economy.

5. Parameters and Model Dynamics

5.1 Estimating Model Parameters

The model described in the previous two sections has 38 parameters. These have been classified into six categories: a) parameters describing agents characteristics; b) parameters describing technology characteristics; c) parameters describing networks; d) macroeconomic parameters; e) environmental parameters; and f) initial conditions (see Table 5.2).

Before we use the model to estimate optimal consumption, savings and investments schedules, it is necessary to estimate the distribution of the these parameters. For some of these parameters, I use estimates from the literature (e.g., the output-capital elasticity in the production function).

For parameters that do not have an empirical counterpart, and that are not important from a theoretical/policy point of view (e.g., the mean and variance of the distribution of agents in the one dimension geographic space), I have fixed arbitrary values (these parameters have the label "subjective" in the source column). I have estimated the other parameters through moments simulation (for other applications of this method, see Robalino and Lempert, 1999; Dowlatabi and Oravetz, 1997; Akerloff et al. 1996; and Meijers, 1994). The main idea is to search for a set of model parameters that generate model dynamics that satisfy basic data constraints. I have limited myself to set three types of constraints: i) the distribution of GDP growth rates during the period 1984-1994 (given our assumption that the growth rate of the labor force is given by the growth rate of the population this is equivalent at looking at the growth rate of labor productivity); ii) the distribution of the growth rate of the ratio between GDP and the consumption of oil and carbon during the same period of time; and iii) historical rates of technology diffusion.

Description	Symbol	Values or Prior Distribution	Source
Agents			
Variance in the distribution of capital per capita (% of the mean capital per capita)	V_k	~N(200,200)	Deininger and Squire (1998).
Mean and variance of the distribution in the one-dimensional geographic space.	c,Vc	100,30	Subjective
Mean and variance of the distribution of risk aversion	λ, σ_λ	0.5,0.01	Robalino and Lempert, 1999
Adjustment factor in learning model	RR	0.5	Subjective
Technologies			
Output elasticity of capital	α	0.4	Pizer (1998)
Elasticity of substitution for old technology	ρ	~U[0.2,0.6]	Dowlatabi (1997)
Relative elasticity of substitution of the new to the old technology $\rho_{new} = \rho_{old} * (1+u)$	u	~U[0,0.1]	
Weight in CES function	a	0.5	Edwards, (1991)
Depletion rates for old and new technologies (old=1)	ξ	~U[0,5]	On the basis of Manns and Ritchels, 1988
Cost of first unit expressed as % of GDP if all agents switch.	$\tilde{\Lambda}_o$	~U[1,120]	Tavoulareas and Charpentier (1995)
Domestic learning coefficient	b_1	~U[0,0.3]	Christianson (1995)
International Learning Coefficient	b_2	~U[0,0.03]	On the basis of productivity growth estimates by Pizer (1998)
Variance of the random shock in learning function	σ_u	~U[0,0.1]	On the basis of productivity growth estimates by Pizer (1998)
Networks			
Connectivity	β_1	~U[0,0.5]	On the basis of connectivity and Ethno-linguistic fractionalization index.

Table 5.3: Model Parameters.

Description	Symbol	Values or Prior-Distribution	Source
Innovation size	ψ_0	~U[0,0.1]	On the basis of productivity growth estimates by Pizer (1998)
Innovation rate	ψ_1	0.01	On the basis of productivity growth estimates by Pizer (1998)
Quality of Connections	ψ_2	0.5	
Innovation rate in old technology	ψ_3	0.3	Subjective
Cooperative behavior	χ	~U[0,0.9]	Subjective
Spillovers	β_2	~U[0,0.3]	Christianson (1995)
Macroeconomic and Institutional Parameters			
Population growth	φ	0.01	
Inertia in the labor market	ω	0.9	Akerloff et al. (1996)
Discount rate	θ	1.025	Cline, (1993)
Depreciation of the stock of produced capital	δ_k	5%	Pizer, (1998)
Environmental Parameters			
Minimum threshold	δ_1	given by initial conditions	Subjective
Damages at the threshold (%GDP)	δ_0	~U[1,10]	Taking as reference catastrophic estimates of damages from climate change (see Cline, 1993).
Growth rate of damages below the threshold	δ_2	1.3	Cline, 1992
Regeneration of the stock of natural capital	R	~U[0,0.1]	Subjective
Initial Conditions			On the basis of World Bank (1998b)
Depletion rate for fossil fuels		U~[0.05,0.6]	
Capital per Capita		U~[100,2000]	
ICOR (GDP/K)		U~[0.1,1]	
Savings rate		U~[0.10,0.35]	
Stock of oil and carbon per capita (USD (1987) per capita)		?	
Exports (% GDP)		20%	
Imports (% GDP)		20%	
Non Education expenditures (% GDP)		5%	
γ_1 γ_2		~U[-0.001,0.001] ~U[0,0.1]	

Table 5.3: Model Parameters (Continuation).

Given that my objective is to calibrate the model to an average developing country, I have included as parameters initial conditions (e.g., initial GDP per capital, initial stock of produced capital per capita, initial depletion rate for fossil fuels). Hence, the joint distribution of model parameters also controls for different initial conditions.

To proceed with the estimation it is first necessary to define a prior-distribution for each model parameter to be estimated. I have defined these distributions on the basis of evidence from the literature, or as in the case

of the price for natural resources, on the basis of exploratory analysis of plausible ranges of variation for the model parameters. For instance, a value of γ_1 in equation (5.33) above 0.1 causes unrealistic fluctuations in the long run. In general, I have tried to keep the variance of the prior distributions as large as possible. Also, given little information about priors I have used uniform probability distributions.

The algorithm used in the search conducted 20 cycles of 3,000 iterations (i.e., combinations of model parameters). For each iteration, the mean and variance of the endogenous variables was computed through 200 Monte Carlo. The results of the estimation are summarized in Figure 5.5. The figure presents the distribution of the simulated and observed average growth rates for GDP and the fossil fuels depletion rate. We observe that the model does a good job in replicating observed distributions, although in the case of the growth rate for the depletion rate, it fails to generate very high of very low values.

In the next Chapter I will present a detailed analysis of the effects of model parameters and policy choices on model dynamics. In the next section I limit my self to discuss the effects of the level of networks connectivity

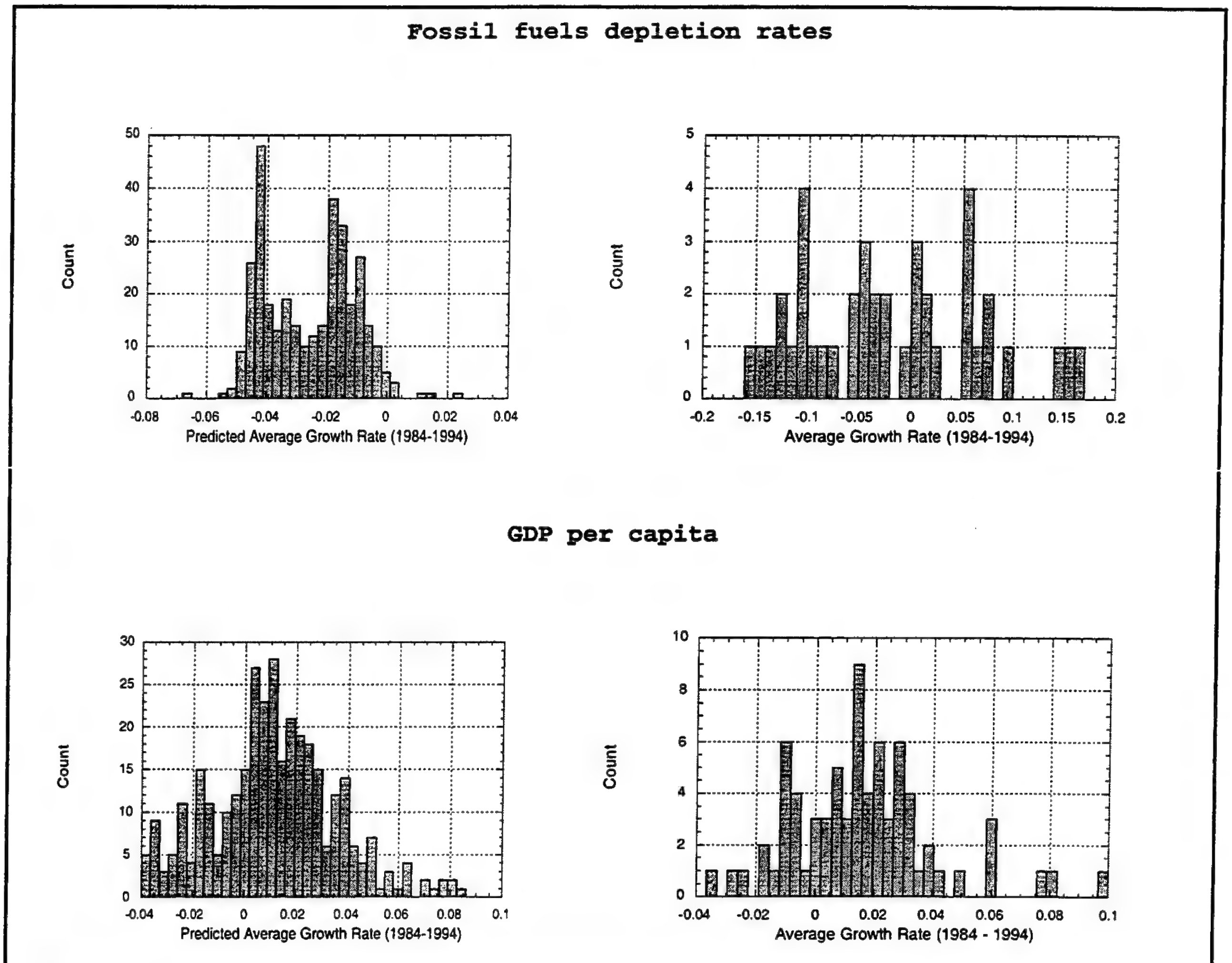

Figure 5.5: Predicted and observed distributions for the growth rates of fossil fuel depletion rates and GDP per capita (1984-1994).

5.2 Networks Connectivity and Steady States

The model developed in the previous sections shares many of the characteristics of the models within the Social Interactions approach that I described in Chapter 3. As in Young's model (1999), the benefits that agents derive from a particular technology depend on the choices of their neighbors. In the absence of coordination, these choices may fail to be socially efficient, given spillover effects. Yet with some probability, that I define here exogenously, cooperation emerges. More important, the model implicitly defines a set of transition probabilities between technology states that

parallels Durlauf (1993). Indeed, the productivity of the new technology for a given agent depends on the previous choices of its neighbors. If most of them are using the new technology, then it is likely that spillover effects will take place, and that for the agent in question, switching to the new technology will be profitable. Thus, as in Durlauf (1993), one can define $\mu\left(w_{it}=1\middle|\mathbf{P}_{t-1}, w_{jt-1}\forall j \in v(i)\right)$ as the probability that an agent will adopt the new technology given the previous choices of its neighbors. Given the relative complexity of our model, starting with the fact that the networks are not regular and fully connected as in Durlauf (1993), I cannot show that his proofs apply. However, I use simulations to analyze the effects that connectivity has on model steady states. Intuitively, one should expect, as in Durlauf, that multiple steady states would emerge and that the model will display non-ergodic properties, in the sense that initial conditions do not fully characterize the steady state that is chosen.

This is indeed what happens when network connectivity increases. In Figure 5.6, I have graphed the range of variation of the steady state level of GDP as a function of the level of connectivity and the frequency and magnitude of technological innovation (parameters ψ_0, ψ_1 in equation 5.20). The dynamics of the model are driven by changes in the stock of produced capital, the supply of labor, the supply of natural resources, and technological progress. Therefore, a pure steady state where neither the economy nor the population are growing, implies a fixed stock of produced and human capital, a constant supply of natural resources, and no technological change. The line in the center can be interpreted as the average level of GDP in the steady state. The top line describes the maximum steady state level of GDP and the bottom line represents the minimum steady state level of GDP. It is clear that as connectivity increases multiple steady states become possible. Hence, the economy can reach high output equilibria (e.g., somewhere along the top line) or low output equilibria. Which equilibria is chosen depends on the series of technology shocks experienced by the economy.

The interpretation of this result if the following. As connectivity increases, information flows regarding technological innovations also increase. However, increased flows benefit both the old and the revolutionary

technology. Therefore, a sequence of positive shocks for the old technology will make it more difficult for the new technology to penetrate the market. Hence, while on average more connected economies have more growth potential (i.e., the average level of GDP of steady state GDP tends to be higher) they may also generate more inertia for the old technology.

The empirical implication of this result is that, other things being equal, countries with high connectivity will face more variability on their long-run levels of GDP. An empirical implication is that the variance of the error term in an econometric model of growth that does not control for connectivity, should increase with the level of connectivity. Therefore one can think about testing the empirical implication of this model, by looking at the relationship of the variance of the residual with the level of connectivity. Given time constraints I have not implemented this test but this is something to keep in mind for future research.

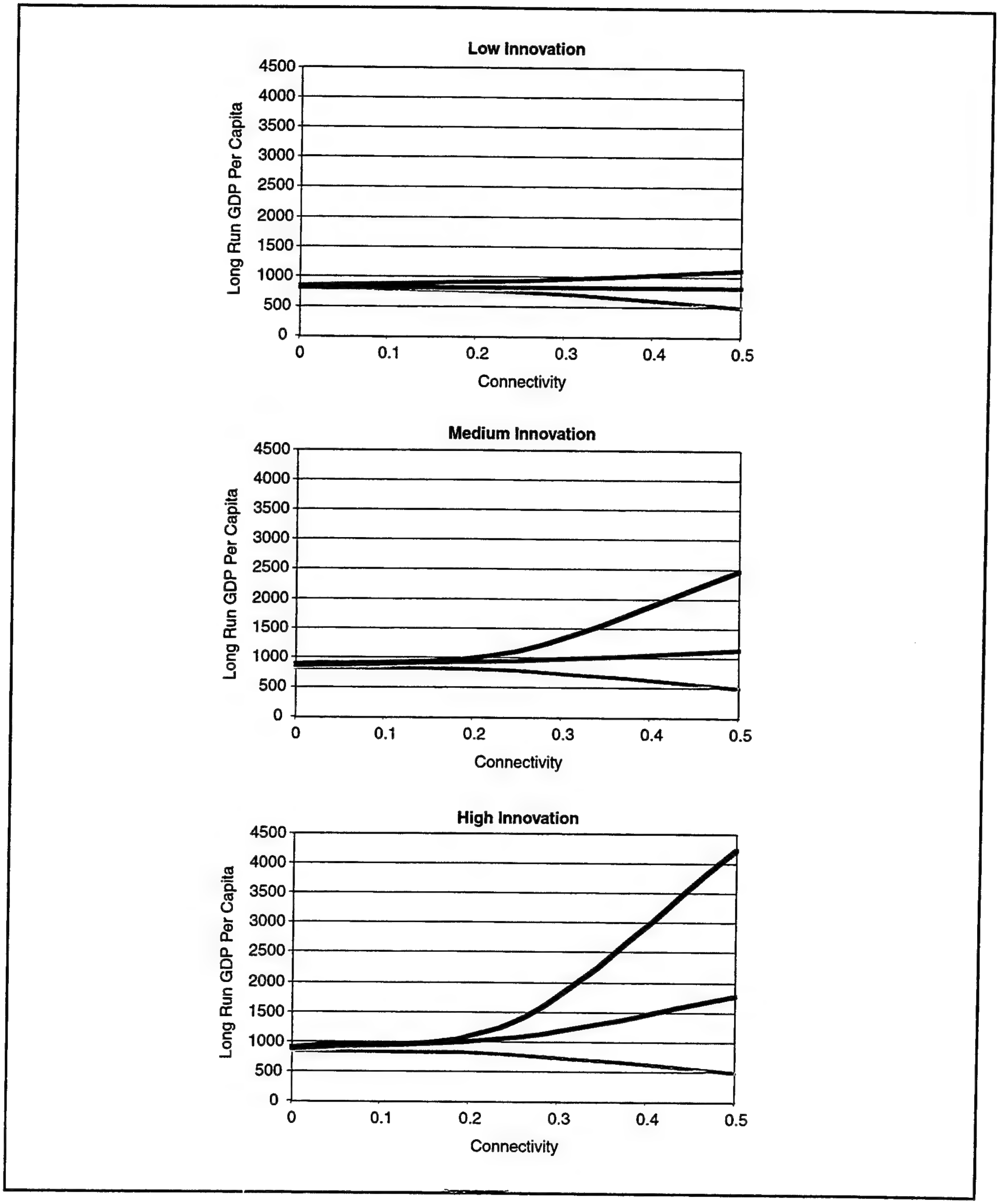

Figure 5.6: Connectivity and GDP Steady States.

6. Conclusion

This chapter has described the construction of an agent-based model of growth with endogenous technology diffusion that emphasize the role of social interactions in agents expectations about the macro-economic environment and the characteristics of new technologies. The chapter has also described the method used to estimate the model parameters. The results show that the model is able to generate consistent dynamics for macro variables of interest. Our analysis has drawn attention on the importance that network connectivity and technology characteristics have for the dynamics of variables such as aggregate output and depletion rates of the economy, and the non-linear character of these relationships. The chapter has also illustrated on the basis of simulations that the model displays non-ergodic dynamics when connectivity and the rate of innovation are high.

The next chapter will use the model to analyze how a benchmark economy facing an environmental constraint should choose savings rates, investments in produced capital, technology incentives, and the consumption of fossil fuels, in order to maximize intertemporal social welfare. The chapter will pay particular attention to the role of network structures in determining these policy choices.

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[1] Other models that have followed this vein of research are Mattson (1997) and Messner (1992).
[2] These coefficients capture the effects of learning by doing and learning by using.
[3] I will be using interchangeably the word "firm" and the word "agent".
[4] Physicists at the Santa Fe institute in New Mexico, have estimated that, on average, each individual is directly related to 300 other individuals (rates are of course higher among politicians or businessmen) [informal conversation with James Cruchtfield].
[5] The use of a probability is of course a shortcut to keep the level of complexity of the model at a minimum. However, the reader is referred to Young (1999), Kranton and Minehart (1999), and Kranton (1996), for more complex formalizations of the process through which cooperation emerges.
[6] This is the so-called "Delta Method" (see Green, 1997).
[7] In the dynamic optimization problem of chapter 6, this saving rate is assumed to be a control variable.

Chapter 6 - Mitigation of Carbon Emissions and Sustainable Growth

1. Introduction

We have seen that sustainable growth usually requires coordinating macro-policies such as the saving rate of the economy with environmental policies generally concerned with the best consumption pattern for the stock of natural resources. Within this stock, fossil fuels are currently receiving high levels of attention at the international level, given that their consumption contributes to the accumulation of CO_2 in the atmosphere, which increases the mean surface temperature of the planet. Some of the potential consequences of this increase in temperature include reductions in agricultural output, an increase in the risk of tropical storms, the rise of ocean levels, and the increase in the prevalence of vector-borne diseases. While the exact costs associated with these responses remain unknown, it is expected that damages resulting from a doubling in the current level of concentrations could be in the order of 2% to 10% of world GDP. Damages vary by region, and may be more dramatic for African countries, where the agricultural response is expected to be particularly severe. However, costs associated with "climate change" are not the only social costs imposed by carbon emissions. Other costs are directly related to health problems (see Beghin et al., 1999, for a macro-simulation analysis of these costs in the case of Chile).

Several studies have addressed the question of how to reduce carbon emissions at the international level (see Robalino and Lempert, 1999 for a review). In this chapter, I will concentrate on the question of how, individually, middle income developing countries should stabilize carbon emissions in order to promote sustainable growth. As in the case of other environmental problems, policy choices will be influenced by expectations about the diffusion of new low-emitting technologies and the dynamics of the economy. Therefore, policies that target reductions in carbon emissions need to be coordinated with macro policies and technology policies. Hence, my analysis uses the model of technology diffusion and growth developed in the previous chapters. I consider three policy instruments: carbon emissions permits, investments in produced capital, and technology incentives. Besides deriving optimal

dynamics for these control variables, I analyze how the optimal paths change as a function of network structures.

The chapter is organized into four sections. Section 2 describes the methodology used to search for optimal paths for the policy variables. Section 3 applies this methodology to find the dynamics of the optimal savings rate for a representative economy. The purpose of this section is to study how the policy recommendations derived from the agent-based model of growth compare to the policy recommendations from a standard stochastic model of growth. Section 4 expands the search initiated in Section 3 by incorporating two additional controls: carbon emissions and the level of economic incentives for new technologies. Finally, Section 5 provides concluding remarks.

2. Numeric Approximation of Optimal Paths for the Policy Variables in the Agent-Based Model of Growth

The model described in the previous chapter does not accept analytical solutions for the optimal path of the policy variables. A numeric procedure is required. Choosing such a procedure implies addressing tradeoffs between costs (computer time) and benefits (precision). An efficient method is one that provides reasonable precision for the lowest cost. The methodology in this section has been chosen under these criteria and is inspired from the work of Pizer (1998), Miller (1998), and Robalino and Lempert (1999).

2.1 Preliminaries

Take a stochastic model $M=(g,\sigma)$, such as ours, and an objective function f that one wishes to maximize. The problem to be solved can be written in continuous time as:

$$\begin{cases} Max: \ E\int e^{-r(t-t_0)} f(\mathbf{x},\mathbf{u})dt \\ s.t. \\ dx = g(\mathbf{x},\mathbf{u})dt + \sigma(\mathbf{x},\mathbf{u})dz \\ \mathbf{x}(0) = \mathbf{x}_0 \end{cases}, \tag{6.1}$$

where $\mathbf{x}$ is a vector of state variables, $\mathbf{u}$ is a vector of control variables, t is time, r is the discount rate and dz is the change of some random process. Assume there is a solution to (6.1), not necessarily unique. This solution needs to be a function of time and the state variables (as opposed to the deterministic problem where the control variables are only functions of time). Then we can write a solution i for (6.1) as:

$$\mathbf{u}(t) = u_i^*(\mathbf{x}(t),t), \tag{6.2}$$

Equation (6.2) defines the optimal response of the controls to realizations of the state variables. Assume that (6.2) is known and that we initialize system (6.1) at time 0 and "let it run" up to time T. This process allows us to generate a sequence $\{\mathbf{u}\}_0^T$ of optimal controls. If we repeat the process N times we can generate N sequences $\{\mathbf{u}\}_0^T$. Thus, given the average dynamics of the system (resulting from N runs), we can compute the average optimal response of the controls at each time t. Indeed, for each control $u_j \in \mathbf{u}$ we can compute:

$$m_j(t) = \sum_{n \in N} u_i(t)/N, \tag{6.3}$$

Notice that $m_j(t)$ does not depend on the states variables. It reflects an average best response given the uncertain dynamics of the system. The basic idea of the numerical procedure is to approximate m(t) without having to derive (6.2). This way, we can define a reference average-optimal path for policy variables and compare, for instance, how this path changes as the model parameters change.

In the numerical application, I work in discrete time and solve the problem in finite time. Because I ignore which is the appropriate functional form for each $m_j(t)$, I proceed as follows. For each m_j define V sub-controls $v_j(k), k \in K = \{t_0, t_0 + \Delta t, t_0 + 2\Delta t, ..., T\}$ with $V = (T - t_0)/\Delta t$. Then we have:

$$m_j(t) \equiv \begin{cases} v_j(t), \ \ if \ \ t \in K \\ v_j(\underline{t})(g)^{t-\underline{t}}, \ \ if \ \ \underline{t} < t < \underline{t} + \Delta t \ \ and \ \ \underline{t} \in K, \ \ g = \left(\dfrac{v_j(\underline{t} + \Delta t)}{v_j(\underline{t})} \right) \dfrac{1}{\Delta t}, \end{cases} \tag{6.4}$$

The smaller the Δt, the higher the precision of the calculations. Basically, (6.4) fixes "points" over m(t) and then extrapolates points that lie between the fixed points.

An optimal policy with j controls can then be written as:

$$P^* = \{v^*_{jk}\} = \begin{matrix} v^*_{10} & \cdots & v^*_{1K} \\ \vdots & \ddots & \vdots \\ v^*_{J0} & \cdots & v^*_{JK} \end{matrix}, \ j \in J, k \in K, \tag{6.5}$$

The numerical procedure starts with a random matrix v_{jk} and iterates to find the matrix (6.5). Policy P* is not necessarily unique. Indeed, this is to be expected given the complexity of our model and the prevalence of non-linear dynamics. Therefore, I will search for a set of policies P* that generate values for the objective function within a given confidence interval.

2.2 Numerical Algorithm

The algorithm belongs to the class of step ascendant algorithms and combines a modified Miller (1998) ANTs with the standard *simulated annealing* algorithm. The algorithm starts with a random matrix v_{jk} (or a best guess matrix if available), then implements the following steps:

1. Computes the expected value of the objective function through Monte Carlo simulation;

2. Compares expected value with the expected value of the best policy, $\text{Max}\, v_{jk}$, currently available (I work with different randomly generated initial policy matrix). If the expected value of the new policy v_{jk} is statistically significantly higher, then update the best policy with probability $1/\exp(-\rho_0 t)$ (where t is the iteration). If the policy is statistically significantly lower or equal then updates the best policy with probability $1-1/\exp(-\rho_0 t)$;

3. Takes the matrix v_{jk} of the best policy currently available and with probability ρ_1 generates a new random matrix. With probability 1-ρ_1 samples controls. Each control has a probability ρ_2 of being sampled. When sampled, a value is drawn from its uniform distribution. Returns to 1.

The performance of the algorithm is calibrated with the parameters: ρ_0, ρ_1, ρ_2 all ranging between 0 and 1. Policies are evaluated through the set of sampled points describe in Chapter 5. Thus, in step 1, the algorithm computes the expected value of the policy v_{jk} across the N points.

2.3 Convergence

Algorithms of the type described above tend to converge to optimal solutions in finite time (see Green, 1992; and Mitchel, 1998). However, the time required is unknown ex-ante. The method that I use to test the robustness of the solutions is as follows. First, I run the algorithm starting from different initial conditions. On average, a given solution is the result of 3,000 iterations (with no repetition). Second, as in Lempert and Robalino (1999), I perform a back search. Hence, I test the optimal solutions by exploring the consequences of changes to each of the policy instruments.

2.4 Implementation

The objective function of the problem is given by:

$$V(C_t)=\sum_t (1+r)^{T-t}\left\{L_t\frac{(C_t/L_t)^{1-\tau}}{1-\tau}\right\}, \tag{6.6}$$

where C is consumption and L is the labor force.

There are three policy instruments: the savings rate of the economy (s), the level of technology incentives (Sb), and the level of carbon emissions (n).

The savings rate s(t) is expressed as a percentage of GDP. These savings are allocated to the creation of produced capital. Technology incentives, Sb(t) are expressed as a percentage of the price of the new technology. Given this value and the demand for new technologies, one can compute the total cost of the subsidy TCS(t) that gets subtracted from GDP. Hence, total consumption at time t is given by the identity:

$$C_t=\left[GDP_t(1-Damages_t)-TCS_t\right](1-s_t), \tag{6.7}$$

I maximize the objective function within a horizon of 50 years. Then, for each control (except the natural resources consumption control), I define Δt=10 and construct 4 sub-controls: $v_{j0}, v_{j10}, v_{j20}, v_{j30}$. I impose the constraint $v_{jt}=v_{j30};\ t>30$. The year 30 is the year when the system starts on average to converge to a steady state. In summary, the policy matrix takes the form:

$$v_{jk}=\begin{matrix} n_0 & n_{10} & n_{20} & n_{30} \\ s_0 & s_{10} & s_{20} & s_{30} \\ sb_0 & sb_{10} & sb_{20} & sb_{30} \end{matrix}, \tag{6.8}$$

To implement the optimization problem, I consider an average developing country with a per capita income of USD (1987) 400, an incremental capital output ratio (icor) equal to 0.4, and a carbon intensity given by 1.7 Kg per unit of GDP (the average for middle income countries in 1995, see Table 6.1).

year	Central America	Caribbean	East Asia Pacific	High Income OECD	Middle East	North Africa	North America	South America	South Asia	Sub-Saharan Africa	Western Europe
1970	0.63	1.30	2.32	0.98	1.15	0.97	1.54	1.74	1.12	0.69	0.90
1971	0.69	1.26	2.36	0.96	1.30	1.04	1.59	1.74	1.07	0.71	0.96
1972	0.71	1.27	2.44	0.95	1.08	1.09	1.53	1.72	0.93	0.72	1.01
1973	0.70	1.51	2.35	0.94	1.23	1.16	1.53	1.81	0.95	0.80	1.10
1974	0.65	1.49	2.32	0.90	1.18	1.15	1.62	1.67	0.91	0.79	1.09
1975	0.70	1.49	2.43	0.87	1.07	1.15	1.58	1.72	0.90	0.75	1.10
1976	0.69	1.71	2.63	0.88	1.12	1.16	1.77	1.71	0.88	0.73	1.12
1977	0.73	1.69	2.69	0.85	1.16	1.19	1.78	1.62	0.94	0.72	1.19
1978	0.75	1.68	2.67	0.84	1.14	1.29	1.92	1.70	0.92	0.76	1.15
1979	0.72	1.70	2.60	0.85	1.29	1.26	1.91	1.71	1.00	0.80	1.16
1980	0.63	1.67	2.37	0.85	1.39	1.31	1.96	1.78	0.99	0.80	1.15
1981	0.59	1.55	2.24	0.80	1.51	1.24	1.94	1.65	1.00	0.78	1.15
1982	0.57	1.56	2.22	0.78	1.64	1.18	2.23	1.68	1.02	0.77	1.19
1983	0.57	1.60	2.23	0.74	1.57	1.25	2.13	1.61	1.03	0.80	1.25
1984	0.53	1.50	2.08	0.72	1.71	1.32	1.99	1.60	1.01	0.80	1.23
1985	0.60	1.68	2.05	0.73	1.77	1.26	1.96	1.46	1.03	0.76	1.31
1986	0.63	1.55	2.00	0.71	1.90	1.32	1.99	1.37	1.04	0.77	1.32
1987	0.66	1.71	1.92	0.70	1.96	1.33	2.05	1.36	1.07	0.86	1.34
1988	0.66	1.55	1.88	0.65	1.90	1.34	2.02	1.44	1.06	0.86	1.23
1989	0.67	1.66	1.83	0.64	1.97	1.29	1.99	1.54	1.05	0.84	1.37
1990	0.66	1.77	1.92	0.64	1.98	1.27	2.06	1.52	1.07	0.85	1.36
1991	0.73	1.92	1.94	0.66	1.98	1.28	2.05	1.47	1.10	0.82	1.30
1992	0.74	1.93	1.91	0.65	1.88	1.28	2.06	1.51	1.13	0.88	1.26
1993	0.75	1.79	1.84	0.62	2.07	1.37	2.02	1.59	1.14	0.85	1.30
1994	0.83	1.71	1.86	0.61	2.06	1.36	2.04	1.56	1.17	0.88	1.34
1995	0.84	1.72	1.82	0.62	2.04	1.37	2.14	1.71	1.16	0.79	1.31

Table 6.1: Dynamics of Carbon Intensities in the World (Kg/GDP 1987).

3. Can We Safely Ignore Social Interactions?

Before tackling the full problem, I concentrate on the question of how important social interactions are in determining optimal savings rates. Hence, I work only with the second row of the policy matrix. That is, I focus on finding an optimal savings rate for a representative economy. I assume that there are no technology incentives. The purpose of this exercise is mainly to compare the policy recommendations from the agent-based model of growth, regarding optimal savings, to the policy recommendations of a standard stochastic growth model. By omitting social interactions, the latter implicitly assumes they are not important. The effects of social interactions in the aggregate, can be seen as noise affecting productivity growth. Implicitly, a stochastic model of growth would take into account these interactions.

The single-representative stochastic growth model that I take as reference is given by:

$$\max: \quad V(C_t) = \sum_t (1+r)^{T-t} \left\{ L_t \frac{(C_t / L_t)^{1-\tau}}{1-\tau} \right\}$$

s.t

$$\begin{aligned} Y_t &= \left(A_t^* N_t\right)^{1-\theta} K_t^{\theta} \\ K_{t+1} &= K_t(1-\delta_k) + (Y_t - C_t) \\ \log(A_t^*) &= \log(A_{t-1}) + \gamma_a e^{-\delta_a t} + \sigma_a \varepsilon_t \end{aligned} \qquad (6.9)$$

where Y is GDP, K is the stock of produced capital, L is labor, C is consumption, δ_k is the depreciation rate of capital, A is labor productivity, γ_a is the productivity growth rate that decays at a rate δ_a, ε are random shocks, and σ_a is the variance of these shocks. The question I ask is whether this simple model can reproduce the dynamics of the agent-based model of growth and then compute optimal savings rates, without having to implement a complicated numerical procedure. This has been the standard practice in

macroeconomic analysis: take an economy, fit a model such as (6.9), and then analyze and recommend policy interventions.

A fundamental difference with the agent-based model of growth is that the production function in (6.9) is replaced by multiple production functions. A second difference is that productivity growth in model (6.9) is defined exogenously (through the last equation), while in the agent-based model of growth it depends on agents' interactions.

It can be shown that the optimal savings rate s* associated with 6.9 is characterized by:

$$\begin{cases} s_t^* = \dfrac{K_{t+1} - K_t(1-\delta_k)}{Y_t} \\ \Delta \ln(K_{t+1}/N_{t+1}) = \alpha_1 + \alpha_2\left(\ln(K_t/N_t) - \ln(A_t^*)\right) \end{cases} \tag{6.10}$$

where α_1 and α_2 are functions of δ_k, θ, the rate of time preference (r), and the coefficient of risk aversion (τ).

To compute the optimal savings rate, I run the agent-based model of growth and use (6.9) to compute at each time t the implicit A(t) associated with the observed level of output and the observed level of capital. Then, I use (6.10) to compute s* and update the stock of produced capital accordingly. I repeat the experiment 1,000 times to be able to compute a 95% confidence interval for this optimal savings rate.

In a second step, I apply the numerical optimization routine described in the previous section to compute the optimal savings rate *directly* from the agent-based model of growth. Both of these savings rates are presented in Figure 6.1. The immediate observation is that the savings rate computed with the aggregate model (6.9) underestimates the optimal savings rate of the economy relative to the agent-based model. The explanation for this is straightforward. *In the aggregate model, there is no direct feedback from the savings rate to the growth rate of productivity*. Hence, the only benefit of saving today is more consumption in the future through an increase in the capital stock. In the agent-based model of growth, an increase in the stock

of produced capital (resulting from savings) tends to be associated with higher productivity growth. This is so because as the stock of produced capital increases, the likelihood of observing adopters of the new technology also increases (see Chapter 5). Because innovations are assumed to occur more frequently in the case of the new technology, adoption by early users generates a knowledge externality. Thus, in our model, savings have in a sense a double effect: they increase the stock of produced capital, but also contribute to faster productivity growth.

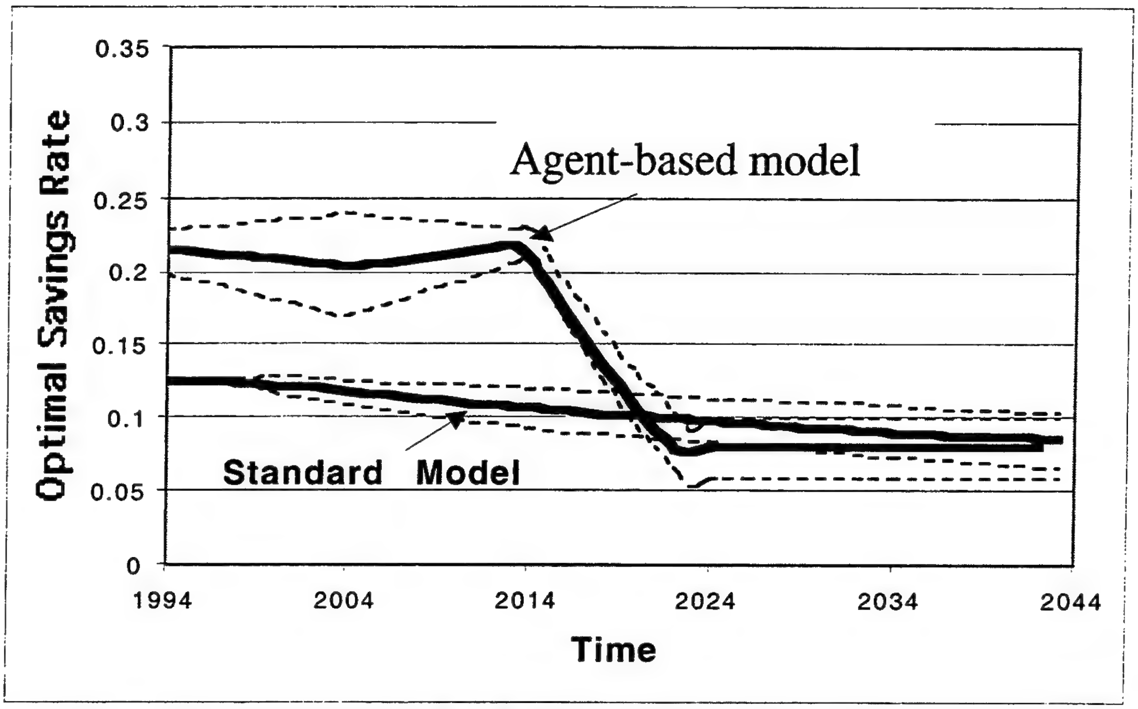

Figure 6.1: Optimal Savings Rate With and Without Social Interactions.

This simple analysis suggests that aggregate models such as (6.9) may be missing an important part of the story, and that policy recommendations derived from those types of models may be biased. In our example, the "optimal" savings rate in the standard model is too low for a quarter century, assuming the agent-based model truly describes the economy. Future research should investigate empirically the impacts of savings on technological change. The results also support the idea that there are benefits from trying to model social interactions in applied models.

4. Savings, Investments in New Technologies and the Consumption of Carbon Emissions

4.1 Theoretical Considerations

At the international level, the optimal consumption of carbon emissions should result from a coordinated action between countries, where each country imposes a tax on carbon emissions that is equal to the discounted value of future marginal social damages resulting from the carbon emissions. To see this, consider the following maximization problem:

$$Max_{n_{i,t}} : \int_{t=0}^{\infty} e^{-rt}\left\{\sum_i Q(n_{i,t}) - D_i(N_t)\right\},$$
$$s.t.\ \frac{dN}{dt} = \sum_i n_{i,t} - \delta_n N \tag{6.11}$$

where $Q_i(.)$is a production function for country i that depends on the consumption of carbon (n), and $D_i(.)$ is a damage function for country i that depends on the stock of carbon in the atmosphere (we assume D'>0, D''>0 so that damages increase exponentially). It can be shown that optimality implies:

$$\frac{\partial Q_i}{\partial n} = \lambda \quad ,$$
$$\lambda = \int_{t=0}^{\infty} e^{-(r+\delta)t} \sum_i \frac{\partial D_i}{\partial T} dt \tag{6.12}$$

Hence, the optimal "tax", λ, will be given by the sum of marginal damages across all countries. Given that the tax is the same but the production functions vary by country, it is clear that the optimal reduction on emissions differs by country[1]. Of course, in the absence of uncertainty, an alternative could be to compute the optimal aggregate reduction on emissions, and then impose that reduction to each country through permits.

The important message is that optimal abatement requires coordination among countries. Unfortunately, there is no guarantee that all countries are likely

to cooperate given the "free-rider problem". Radner (1999) analyzes the question of how to create incentives that promote coordination between countries within a game-theoretical framework. However, little is known about the incentives that individual middle-income economies face to reduce carbon emissions. Here, I will address this question. While in climate models applied at the international level damages are related to the stock of capital, in this single-country analysis, they are directly related to the flow of emissions. Small countries contribute little to the world stock of greenhouse gases, and therefore have no real incentive to reduce emissions on the basis of climate change. Yet, there are other costs that are directly associated to the flow of emissions. For example, those resulting from health problems, or those associated with international sanctions for non-compliance with emissions standards. These costs are of course highly uncertain. Hence, we treat the parameter d_0 of equation 5.26 as a random variable with a broad range of variation (0-10% of GDP for the baseline year). The values have been chosen on the basis of Dixon et al. (1998) that estimates social costs of carbon emissions on the basis of a "willingness to pay" approach. The estimated costs approximate US 0.02 per Kg of carbon, or given our baseline carbon-intensity (1.7 Kg of carbon per unit of GDP), 3.4% of GDP.

Given the complexity of our model, before describing the numerical results, it is useful to build some intuition regarding the impact of the policy instruments on its dynamics. Assume that at time t, the average developing economy under consideration has a level of GDP given by q_t and that damages are D_t. This implies that at time t+1 the level of GDP can be written as:

$$q_t = q_{t-1}(1+g)(1-D_{t+1}), \tag{6.13}$$

where g is the growth rate of the economy in the absence of damages. We know that for any t, $D_t = d_0\left(\frac{\gamma q_t}{z}\right)^{d_1}$, where γ is the carbon emissions/GDP ratio that depends on the market shares of the old and the revolutionary technologies as well as prices. Then, the growth rate of damages can be approximated by $d_1(\dot{\gamma}+g)$ where a point over a variable represents a growth rate. Then we can re-write (6.13) as:

$$q_t = q_{t-1}(1+g)\left[1 - D_{t-1}\left(1 + d_1(\dot{\gamma} + g)\right)\right], \tag{6.14}$$

We observe in (6.14) that other things being equal, an increase in g, the "natural" growth rate of the economy, can reduce GDP through higher damages[1]. Let's treat $\dot{\gamma}$ as a policy variable, which basically regulates the quantity of carbon emissions. If we set $\dot{\gamma}<0$, damages will be reduced. Unfortunately, in equilibrium, this reduction in the quantity of carbon consumed per unit of GDP can only be achieved if the price of carbon increases (notice that when we talk about the "price" of carbon we are talking about the price of the fossil fuel used in the production function, which is the source of carbon emission, plus any tax on the emission). This increase in the price is then likely to reduce g. The net effect will depend on the parameters of (6.14) and the responsiveness of g to changes in γ. In particular, it will depend on the ability of producers to switch to the revolutionary technology, which is less intensive in the use of carbon. Nonetheless, an increase in the market share of the new technology can have an ambiguous effect on economic growth. First, there are two positive effects. One resulting from a reduction in the price of carbon due to a lower demand under the new technology. Another resulting from an increase in the market share of the new technology which contributes to accelerate economic growth given the assumption that the innovation rate is higher for the new technology. However, there is also a negative effect related to a reduction in savings available to invest in produced capital. Indeed, adoption costs need to be financed out of savings. If agents' expectations about the cost and performance of the new technologies are unbiased, their decisions of adopting the new technology will imply a higher pay-off than investing in new capacity (i.e. expanding the stock of produced capital). In this case the positive effects will dominate the negative effects. However, in our learning environment, expectations are not necessarily unbiased, and the negative effect can overcome the positive effects.

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[1] This will occur as long as $D\left(1 + d_1(\dot{\gamma} + g)\right) > \dfrac{g}{1+g}$.

Notice that even under the assumption of unbiased expectations, a subsidy, by "forcing" an increase in the share of a given technology is implicitly reducing the productivity of domestic savings (at least in the short run). Indeed, if the technology in question is economically efficient, agents would adopt without the need of the subsidy. However, in the presence of knowledge spillovers, the subsidy may contribute to reduce the cost of the new technology, ameliorate its performance, and expand its market share, thus compensating its negative impacts.

Now, imagine a sustainable steady state where the economy is not growing after adjusting for damages. The steady state implies that $g^* = \frac{D^*}{1-D^*}$[2] and $\gamma^*, q^* \in \left\{ D^* = \left(\frac{\gamma^* q^* \left(1+g^*\right)}{z} \right)^{d_1} \right\}$[3]. Notice that if damages grow, sustainability requires that the g* grow as well. However, we know that economic growth can not *accelerate* forever. In the long run, it is more likely that the economy will be growing at a constant rate that is equal to the rate of technological progress. Hence, in the long run, damages and emissions are constrained by the rate of technological progress. Let's denote by E* the level of emissions consistent with the rate of technological progress g*. We know that in the steady state, $E^* = \gamma^* q^* \left(1+g^*\right)$ needs to hold. This implies that a benevolent policymaker could chose *alternative* combinations of output and carbon-emission intensities that solve for the steady state. The goal is to make this choice in order to maximize inter-temporal social welfare.

[2] Indeed, we know that in the steady state $q^* = q^*\left(1+g^*\right)\left(1-D^*\right)$. This implies $\left(1+g^*\right)\left(1-D^*\right)=1$

[3] This is simply the definition of damages with each variable adopting its steady state value.

While I have described a case where damages are cumulative, in the sense that the shocks to GDP at time t persist in the long run, I will work under the assumption that damages only affect consumption, and not the accumulation of capital. This assumption simplifies enormously the interpretation of the results since the growth rate of the economy becomes independent of damages. In other words, the growth rate of the economy will solely be a function of the growth rate of labor and carbon emissions (the production inputs), the savings rate, and productivity growth. While different growth rates for carbon emissions generate different growth rates for damages, these will not affect the growth rate of GDP. The assumption also allows me to be consistent with other models addressing the issue of how stabilize emissions.

4.2 Results for Selected Policies

The policy landscape associated with the optimization problem displays large "plateaus" and multiple peaks. This implies that there is no single combination of the control variables that maximizes the objective function. I have considered as optimal policies all of those that generate values for the objective function within 10% of the maximum value. Table 6.2 presents means and standard deviations for selected endogenous variables under the average optimal policy intervention and selected sub-optimal policy interventions. These sub-optimal policies have been chosen to illustrate the effects of alternative modifications to the optimal policy. I discuss each of these policies in turn.

Policy Matrix	Optimal Policy				Stabilization in the Long Run without Subsidy			
	Year 0	Year 10	Year 20	Year 30	Year 0	Year 10	Year 20	Year 30
Subsidy (%)	10	50	5	5	0	0	0	0
Savings (%)	35	30	25	15	35	30	25	15
Emissions (kg. of carbon)[1]	1360	1657	1500	1300	1360	1657	1500	1300
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Expected Utility	500,081	404	493,098	511,689	494,720	368	488,192	506,446
Equivalent Loss in Consumption	0%				6%			
Growth Rate								
Year 0-10	2.700	0.021	2.240	3.240	2.644	0.021	2.240	3.210
Year 10-20	0.397	0.033	-0.290	1.960	-0.357	0.031	-0.740	1.260
Year >20	0.206	0.090	-0.440	3.800	0.142	0.101	-0.550	4.150
Damages								
0-10	5.446	0.343	0.010	11.540	5.446	0.343	0.010	11.540
10-20	5.682	0.358	0.010	12.040	5.682	0.358	0.010	12.040
>20	4.579	0.288	0.010	9.700	4.579	0.288	0.010	9.700
Share New Technology								
Year 10	24.261	1.315	0.000	35.660	17.767	1.482	0.000	34.700
Year 35	59.618	3.045	0.000	82.780	44.379	3.638	0.000	82.720
Year 50	67.856	3.429	0.000	92.500	51.359	4.087	0.000	92.280
Carbon Intensity								
Year 0-10	0.150	0.000	0.150	0.160	0.150	0.000	0.150	0.160
Year 10-20	0.126	0.000	0.120	0.130	0.117	0.000	0.110	0.120
Year >20	0.091	0.001	0.080	0.100	0.077	0.000	0.070	0.080

Policy Matrix	Stabilization today without Subsidy				Stabilization today with Subsidy			
	Year 0	Year 10	Year 20	Year 30	Year 0	Year 10	Year 20	Year 30
Subsidy (%)	0	0	0	0	20	15	10	5
Savings (%)	35	30	25	15	35	30	25	15
Emissions (kg. of carbon)[1]	1360	1360	1500	1250	1360	1360	1500	1250
	Mean	Std. Dev.	Min	Max	Mean	Std. Dev.	Min	Max
Expected Utility	491,790	366	485,173	503,198	495,145	377	488,150	505,770
Equivalent Loss in Consumption	8%				5%			
Growth Rate								
Year 0-10	1.965	0.019	1.610	2.520	2.689	0.022	2.240	3.210
Year 10-20	0.192	0.033	-0.180	1.760	-0.316	0.033	-0.760	1.300
Year >20	0.166	0.100	-0.520	4.190	0.184	0.104	-0.550	4.220
Damages								
0-10	4.716	0.297	0.010	9.990	4.716	0.297	0.010	9.990
10-20	4.317	0.272	0.010	9.150	4.317	0.272	0.010	9.150
>20	3.283	0.207	0.010	6.960	3.283	0.207	0.010	6.960
Share New Technology								
Year 10	17.313	1.485	0.000	35.100	23.418	1.406	0.000	35.260
Year 35	43.867	3.654	0.000	82.660	55.088	3.384	0.000	83.040
Year 50	50.719	4.104	0.000	92.040	62.575	3.789	0.000	92.400
Carbon Intensity								
Year 0-10	0.140	0.000	0.140	0.140	0.150	0.000	0.150	0.160
Year 10-20	0.110	0.000	0.100	0.120	0.117	0.000	0.110	0.120
Year >20	0.077	0.000	0.070	0.090	0.077	0.000	0.070	0.080

[1] 1360 = 1.7 kg. of carbon * USD (1987) 400 GDP per capita * 2,000 initial population

Table 6.2: Results of the Dynamic Optimization Problem.

Policy Matrix	Unbounded Growth			
	Year 0	Year 10	Year 20	Year 30
Subsidy (%)	0	0	0	0
Savings (%)	35	30	25	15
Emissions (kg. of carbon)[1]	1360	3527	9149	11153
	Mean	Std. Dev.	Min	Max
Expected Utility	461,909	462	282,891	601,567
Equivalent Loss in Consumption	33%			
Growth Rate				
Year 0-10	5.585	0.029	5.050	6.290
Year 10-20	5.326	0.057	4.540	6.950
Year >20	0.896	0.029	0.570	2.160
Damages				
0-10	9.922	0.624	0.020	21.020
10-20	34.254	2.156	0.070	72.570
>20	70.110	4.412	0.150	148.530
Share New Technology				
Year 10	20.119	1.494	0.000	35.340
Year 35	50.661	3.580	0.000	83.480
Year 50	56.476	4.011	0.000	92.540
Carbon Intensity				
Year 0-10	0.200	0.000	0.190	0.210
Year 10-20	0.282	0.002	0.250	0.300
Year >20	0.276	0.003	0.210	0.320

[1] 1360 = 1.7 kg. of carbon * USD (1987) 400 GDP per capita * 2,000 initial population

Table 6.2: Results of the Dynamic Optimization Problem (Continued).

The optimal intervention: reduce carbon emissions tomorrow and implement technology subsidies today

The first column of the top of Table 6.2 summarizes the main characteristics of the optimal policy intervention. First, the intervention is characterized by an increase in emissions at around 2% per year during the next decade. Only then do emissions start to decrease, thus reducing the carbon intensity of the economy. This result is consistent with the Penayotou et al. (1999) proposition of not reducing the carbon intensities of developing economies, particularly those with an income per capita below USD 1,000. Hence, in the short-run, given uncertain damages, developing countries appear to have little incentive to reduce carbon emissions (we remind the reader that we have used a wide distribution for the damages' parameter that ranges between 1% and 10% for the baseline year). The interpretation of this result is straightforward. In our model, economic growth is determined by the growth rate of labor and carbon emissions (the two production inputs), the investment rate, and productivity growth. On the other hand, consumption and therefore utility,

depends on GDP but also the level of damages. Given a distribution of production technologies and a growth rate for the labor force, a slowdown in the growth rate of carbon emissions will slow down economic growth by a factor Ψ that depends on the parameters of the production function. Damages, on the other hand, will be reduced in proportion to the exponent of the damage function, d_1, and the current level of damages D. Formally, the growth rate of consumption at any point in time is given by[4]:

$$\dot{C} = \dot{q} - \left(\frac{1}{1-D}\right)\dot{D} = \psi\dot{n} - \left(\frac{1}{1-D}\right)b_1\dot{n} \tag{6.15}$$

Hence, a reduction in carbon emissions $\dot{n} < 0$ will be more likely to increase consumption when Ψ (which depends on the productive structure of the economy) is high and/or when D (observed damages) is high. Since damages grow, reductions in carbon emissions will tend to be more efficient in the future.

However, delayed mitigation of carbon emissions is not the only key to the strategy. A second characteristic of the optimal policy is the use of technology incentives. In this application, these incentives take the form of subsidies. The subsidy starts at levels of 10% of the cost of the technology (treated as an uncertainty), and increases gradually to 50%. This subsidy stimulates the adoption of new technologies by early users and thus promotes knowledge spillovers that facilitate further diffusion of the technology (of course, as we will see in the next section, the net effect of the subsidy depends on technology characteristics and network structures). Hence, in all time periods, the average market share of the new technology is higher under this policy. A higher share of the new technology implies that more output can be produced with the same level of labor, capital, and carbon emissions, given that the new technology is less intensive in carbon (i.e., the parameter ξ in equations 5.1, 5.2 and 5.6 in Chapter 5 is higher). Because the innovation rate for the new technology is higher, the subsidy also accelerates indirectly the rate of productivity growth. These combined effects help the

[4] We know that consumption is given by $C = aq(1-D)$ where a is the propensity to consume which depends on model parameters. The growth rate of consumption under the assumption that a does not grow is therefore given by equation (6.15).

economy to better accommodate reductions in carbon emissions that contribute to reduce damages.

The importance of the subsidy can be illustrated by "running" the optimal policy without the subsidy. The results for this new policy are presented in the second column of the top of Table 6.2. We observe that the average growth rate of the economy is lower after the 10th year, and even negative during the second decade of the simulation. Damages, on the other hand, remain the same since the path for emission has not changed. As a consequence, expected utility is reduced by an equivalent of 6% of consumption. This difference in performance can be explained by a lower average share of the new technology in all periods.

In the short run, optimal investments in produced capital average 35% of GDP. In the long run, they converge to 15% of GDP as a result of diminishing returns to capital. We are tempted to compare the optimal genuine savings rate with observed genuine savings rates. In Chapter 2, we saw that investments in produced capital were approximately equal to 20% of GDP. This implies that savings rates are really on average 10% lower than optimal savings rates. This result, however, needs to be interpreted with caution, since it depends on our assumptions regarding the structure of the model of technology diffusion. We notice that the steady state savings rate is 5 percentage points higher than in the case with no technology incentives and damages analyzed in Section 2. The explanation is that subsidies are financed through savings, and therefore justify a higher saving rate in return for a higher share of the new technology that will bring faster economic growth.

Restrictions on emissions today will decrease inter-temporal social welfare

The two columns of the medium part of Table 6.2 present the results of policy interventions that stabilize the consumption of natural resources immediately, with and without subsidies. Stabilizing carbon emissions reduces expected utility by an equivalent of 8% of consumption when subsidies are not used. While damages are lower, economic growth is also lower. However, it is interesting to observe that reducing carbon emissions today with subsidies causes a loss in consumption of 5%, which is a slightly better alternative

than reducing carbon emissions tomorrow without the subsidy (see second column of the top of Table 6.2).

Inaction is the worst alternative

While delaying stabilization appears as the optimal policy, the delay should not be extended forever. The last column at the bottom of Table 6.2 presents the results of a catastrophic scenario where carbon emissions are allowed to grow without boundaries. While the rate of economic growth is considerably higher than in other scenarios, at least during the first two decades, social utility is reduced by an equivalent of 33% of consumption. This is the result of the economy not reducing its depletion rate so that damages grow, on average, to levels of 70% of GDP.

4.3 Social Capital, Policy Choices and Empirical Implications

The results described in the previous section refer to an average best response given uncertainty in model parameters. Roughly speaking, the expected performance of a given policy is the average of the performance at each point sampled from the joint distribution of model parameters (see Chapter 5). By averaging across points, we lose the insights of knowing which structural factors, determined by model parameters, favor one policy over another. This is the question that I address in this section on the basis of an econometric analysis of some of the simulation results. My focus will be on the effects that network classes have on policy choices.

The optimization algorithm generates a database that can be exploited econometrically to derive insights about model dynamics and the interactions of model parameters and policy choices. Because the database is generated within a controlled experiment, we are able to observe the distribution of the endogenous variables of interest (e.g., mean and variance) and not only one "realization" which is the case in most empirical analysis. Indeed, for each combination of model parameters, the distribution of the endogenous variables is computed through Monte Carlo simulation. Therefore, this type of database is the dream any econometrician.

I am interested in understanding how model parameters and policy choices affect social welfare. Therefore, I estimate a model of the form:

$$\log U = \psi_0 + \sum_{i=1}^{k} \psi_i \theta_i + \sum_i \sum_j \psi_{k+ij} \theta_i \theta_j + u\,, \qquad (6.16)$$

where U is the utility, θ is a vector of model parameters, including binary variables that characterize policy choices, k is the total number of parameters and policies, and the ψ_i, are coefficients to be estimated.

I work with only three types of policy interventions: the optimal policy, the optimal policy without the subsidy, and a policy that lets carbon emissions grow forever at a rate of 2% per year. These policies are represented by two dummy variables that I call *taxSub* (for the optimal policy) and *tax* for the optimal policy without the subsidy. The third policy is the reference category. Given that the variance of the endogenous variable varies with each realization of the model parameters, I estimate the model through weighted least squares.

The results of two model formulations are presented in Table 6.3. The difference between the two models is that the second ignores the square term of the connectivity parameter (β_1).

N=3,000						
R-squared		0.9403			0.9396	
Parameter	Coefficient	Std.	P-value	Coefficient	Std.	P-value
ρ	0.0320	0.0012	0.000	0.0322	0.0012	0.000
u	-0.0543	0.0157	0.001	-0.0548	0.0158	0.001
$u.\rho$	-0.1257	0.0207	0.000	-0.1253	0.0208	0.000
b_1	0.0404	0.0056	0.000	0.0391	0.0056	0.000
b_1^2	-0.0555	0.0180	0.002	-0.0532	0.0181	0.003
b_1	0.1467	0.0437	0.001	0.1511	0.0439	0.001
b_1^2	-1.9271	1.3374	0.150	-2.1056	1.3429	0.117
σ_u	-0.0028	0.0041	0.497	-0.0020	0.0041	0.617
$\tilde{\Lambda}_o$	0.0000	0.0000	0.012	0.0000	0.0000	0.012
$\xi.\tilde{\Lambda}_o$	-0.0001	0.0000	0.000	-0.0001	0.0000	0.000
ξ	0.0089	0.0032	0.006	0.0093	0.0032	0.004
ξ^2	0.0238	0.0023	0.000	0.0234	0.0023	0.000
ξ.d0	0.0006	0.0002	0.005	0.0005	0.0002	0.007
d0	-0.0022	0.0002	0.000	-0.0021	0.0002	0.000
d0.tax	0.0017	0.0001	0.000	0.0017	0.0001	0.000
d0.taxSub	0.0017	0.0001	0.000	0.0017	0.0001	0.000
$\beta_1$taxSub	-0.0044	0.0080	0.578	-0.0224	0.0059	0.000
$\beta_1$taxSub2	0.0082	0.0150	0.586	0.0426	0.0109	0.000
$\beta_1$tax	-0.0018	0.0082	0.826	-0.0197	0.0062	0.002
$\beta_1$tax2	0.0056	0.0152	0.714	0.0399	0.0113	0.000
$\tilde{\Lambda}_o$taxSub	0.0000	0.0000	0.000	0.0000	0.0000	0.000
ξ.taxSub	-0.0038	0.0014	0.006	-0.0038	0.0014	0.006
$b_1$taxSub	0.0002	0.0029	0.952	0.0007	0.0029	0.823
$b_2$taxSub	-0.0123	0.0275	0.653	-0.0109	0.0276	0.693
tax	-0.0349	0.0011	0.000	-0.0333	0.0009	0.000
taxSub	-0.0329	0.0015	0.000	-0.0314	0.0014	0.000
β_1	-0.0202	0.0062	0.001	-0.0016	0.0027	0.556
β_1^2	0.0354	0.0106	0.001			
$\beta_1\tilde{\Lambda}_o$	0.0000	0.0000	0.937	0.0000	0.0000	0.946
$\beta_1\psi_0$	0.0039	0.0293	0.894	-0.0003	0.0294	0.991
ψ_0	0.0259	0.0094	0.006	0.0264	0.0094	0.005
β_2	0.0059	0.0014	0.000	0.0054	0.0014	0.000
constant	13.1275	0.0020	0.000	13.1258	0.0019	0.000

Table 6.3: Effects of Model Parameters and Policy Choices on Social Welfare.

For clarity, I have organized the table into four sections. The first section includes the parameters that describe technology characteristics, the second

section the damage parameter, the third section the parameters that describe policies, and finally the last section includes the parameters that describe networks. Interactions with no effect on the model performance have been excluded.

I do not comment on all parameters and interactions since some of the relationships are obvious. For example, the productivity parameter ξ increases social welfare (more output can be produced with the same amount of carbon), but its positive effect is reduced by the cost of the new technology Λ_0. However, there are other, less obvious results. First, in both models, we observe an interesting non-linear relationship between the parameters describing the dynamics of the cost of the new technology b_1, b_2 and social welfare. Higher increasing returns to scale are associated with higher social welfare. However, when increasing returns are too high, there may be negative impacts. These can be explained by the reductions in savings, and therefore economic growth, that are associated with the diffusion of the new technology.

In terms of the policy interventions, we observe that the net effects of the tax and tax & subsidy policies are negative. Not surprisingly, introducing subsidies or taxes, for no reason, reduces social welfare. The interactions of the policy variables and damages, however, are positive. Hence, other things being equal, as damages increase, the tax and the subsidies become efficient interventions. We also observe that the higher the cost of the new technology, Λ_0, the better the performance of the tax & subsidy intervention. On the contrary, the lower the carbon intensity of the production technology (i.e., the higher ξ), the lower the positive effect of the tax and the subsidy.

In terms of the parameters describing networks, we observe that social spillovers (β_2) and the innovation rate (ψ_0) are positively related to social welfare. In the first model, we find that the connectivity parameter (β_1) has a non-linear effect on social welfare. The reasons why this may be the case have been discussed before. Connectivity does not necessarily favor the new technology, and even when it does, the diffusion of the new technology does not always favor social welfare. Nonetheless, when we eliminate the squared

term in the second model, the connectivity parameter loses statistical significance, while the interactions of this parameter with the policy variables become significant. This suggests that in the absence of taxes and subsidies, the network's connectivity has little effect on social welfare. As we saw in Chapter 5, high levels of connectivity can be associated with high or low levels of output. The average may be higher, but its variance will be higher as well. Hence, in the weighted model these observations receive less importance. Therefore, connectivity appears to be important for social welfare only in the presence of tax or subsidy policies.

In the second model we observe that the performance of the tax and subsidy interventions is favored with high levels of connectivity. However, other things being equal, low levels of connectivity reduce the positive effects of the tax. This result could have been expected. An environment with high levels of information flows facilitates the adoption of the new technology in the presence of a tax or a subsidy (both interventions reducing the cost of the new technology relative to the old technology), and therefore accommodates the negative impacts of the tax and the subsidy. The implication, however, is less trivial: *subsidies and taxes are less likely to work where they are most needed*. Indeed, in poor countries with low levels of social capital, subsidies are less likely to be efficient, *even after controlling for increasing returns to scale in the production of new technologies* (the traditional justification for subsidies).

The corollary is that subsidies should not be used indiscriminately. Previous to their use, means of increasing social capital should be explored.

A more general implication of this analysis is that the effectiveness of alternative policy interventions does depend on structural conditions. Some of these are obvious and relatively easy to measure (e.g., parameters of the production function). Others, such as network structures, are less easy to measure but equally important. Hence, applying a policy that increases social welfare in a given socioeconomic system may decrease social welfare in another.

5. Conclusion

This chapter has addressed the question of how middle income developing economies should allocate investments in produced capital, savings, and the consumption of carbon emissions in order to maximize inter-temporal social welfare. The analysis was based on the model of technology diffusion and growth developed in Chapter 5. The chapter started by developing a methodology to solve numerically the dynamic optimization problem. The methodology was first applied to compute the optimal savings rate of the economy. The results were compared to those derived from a standard stochastic model of growth with a single representative consumer. We showed that when social interactions are taken into account, the optimal savings rate of the economy increases. The reason is that higher savings induce innovation through an increase in produced capital. In the presence of knowledge spillovers, new adopters contribute to speed up the process of technology diffusion, and thus increase productivity growth. Hence, the benefits of higher savings are not limited to more produced capital and growth, but also to higher productivity growth.

The analysis of optimal mitigation policies showed that small developing economies face no incentive to reduce carbon emissions in the short run. This conclusion is robust for a wide range of values of the parameters characterizing the damage function. Indeed, reductions in emissions have two effects. First they increase the share of non-saved GDP that can be consumed, given that damages decrease. Second, they slow down economic growth, and therefore the share of GDP that can be consumed. In other words, reductions in emissions increase the share of the pie that can be consumed, but also decrease the total size of the pie. We showed that mitigation efforts are more likely to succeed when damages are high, and when the response of the economy growth rate to the growth rate of carbon emissions is reduced.

The support of new technologies through subsidies can generate the latter effect. Hence, in the optimal intervention, mitigation of carbon emissions is delayed while new technologies are subsidized. This appears to be the optimal intervention even in the presence of high levels of uncertainty in the

characteristics of the new technology, in particular its first unit cost, the potential for cost reductions, and its carbon intensity.

Given a trajectory for the consumption of carbon emissions, a higher market share for the new technologies with lower carbon intensity, is associated with higher levels of output and higher productivity growth. The downside of the subsidy is its cost in terms of forgone investments in produced capital. However, spillover effects associated with increasing returns to scale and social interactions may overcome these costs.

The analysis was implemented taking as given a joint distribution of model parameters. Hence the optimal policy described is the optimal policy on average, but it is not the best policy in each of the sampled points. The econometric analysis implemented in the last part of the chapter suggested that there are key interactions between policies and model parameters. One of the main insights from this analysis is that subsidies operate better in societies with high level of social capital. In the absence of social capital, the subsidy may have negative impacts on social welfare, *even after controlling for increasing returns to scale in the production of new technologies*.

The major implication is that optimal policies will vary widely depending on the environment where they are applied. Hence, optimal policies derived for countries with low levels of social capital should be expected to be very different from policies derived for countries with high levels of social capital. Thus, policymakers should use extreme caution when implementing policies derived from models that entirely ignore social interactions. Our results suggest that better policy analysis will be necessarily related to a better understanding of social network structures.

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[1] This problem is more complicated when we consider equity issues. To date, there is no agreement on which should be the mechanism used to distribute carbon reductions across countries (see Panayotou et al., 1999 for an analysis of this issue). One suggestion is that emissions be proportional to the share of damages imposed and assumed by the country.

Chapter 7 - Summary of Findings and Policy Recommendations

1. Introduction

This study examines the role of social capital on the diffusion of new technologies and sustainable growth, and its effects on policy choices. The research started by reviewing macro indicators that could be used to monitor progress towards sustainable growth and evaluated the effect of different economic and social variables on the natural resources intensity of developing economies. The research then developed an integrated economic model for the analysis of policies aiming to promote sustainable growth. This model endogenizes the process of technology diffusion by formalizing the role of social interactions and learning. The model was used to analyze the question of how governments should coordinate macroeconomic policy, technology, and the consumption of carbon emissions, in order to promote sustainable growth. This closing chapter summarizes the main methodological and policy insights resulting from the analysis. The chapter is organized in three sections. Section 1 deals with the methodology. Section 2 deals with policy issues. Finally, Section 3 discusses future research.

2. Macroeconomic Modeling and Sustainable Growth

The integrated assessment community relies on macro-econometric models with different degrees of complexity to inform policymakers. Some of these models have attempted to endogenize technological change in one way or another, but have usually ignored the process of technology diffusion. Implicitly, this is equivalent to the assumption that diffusion is an instantaneous process. Given the importance of the technological factor for the analysis of sustainability, this is not a trivial flaw. In this research, I have argued that in order to generate a better representation of the technology diffusion process - and therefore technological change in general - analysts should move away from the single representative agent paradigm. Indeed, I claim that one cannot really endogenize diffusion without considering social interactions. These interactions are at the core of the process through which agents learn,

and learning is the basis of the diffusion process. The research has also shown that changing paradigm is not without difficulties. This section summarizes the main lessons.

2.1 Why Is It Important for Policy Analysts to Model Micro-Behavior and Let Macro-Behavior Emerge?

By aggregating microeconomic behavior into the actions of a single representative agent, macroeconomic models lose the ability to treat social interactions. Few will disagree with the claim that these interactions influence our behavior and choices. The real question is *how important* are they, and how necessary is it to incorporate them into our models; in particular in the models that we use in policy analysis? Modeling these interactions implies adding a layer of complexity, which comes at a cost. Incurring this cost can only be justified if it is lower than the benefits that result from a better type of policy analysis. These costs and benefits are not easily quantifiable. However, this research provides three rationales for why one should expect that the benefits will more than outweigh the costs.

First, my review of the literature on social capital provides some empirical evidence, with varying degrees of robustness, that the magnitude and frequency of social interactions are important predictors of macroeconomic phenomena, such as economic growth, the diffusion of new technologies, or the depletion rate of the economy (see Chapter 2). One of the reasons is that these interactions generate knowledge spillovers and determine the emergence of cooperative behavior. Common sense suggests that if measures of social capital are important explanatory factors of aggregate phenomena, they should be taken seriously within policy analysis.

A second reason comes from the analysis in Chapter 6. There, I illustrated that single representative agent models can generate policy recommendations that are biased when applied to environments with social interactions. For example, I showed that the representative agent model underestimates socially optimal savings rates. The error of the representative agent policy can be as high as 7% of GDP. Chapter 6 also showed that optimal policy interventions

are, in general, very sensitive to network structures. Networks with low connectivity will generally lead to different policies than networks with high connectivity. Since the real world resembles an environment with interactions, policy recommendations derived from models with a single agent may carry an important bias.

A third reason has to do with model dynamics. Single agent models are usually characterized by well-defined steady states. Policies can be evaluated in terms of how they change this steady state. However, Chapter 5 showed that the dynamics of a macro-model that incorporates social interactions generates a continuum of steady states. Furthermore, dynamics tend to be non-ergodic in the sense that initial conditions do not determine which equilibrium is chosen. In other words, there are high levels of uncertainty surrounding model dynamics as well as the effects of alternative policy interventions. Again, if this is the way the world operates, then policy recommendations derived from models that consider uncertainty only at the level of the model parameters may be very fragile. This type of policies will also do a poor job in reducing the chance of observing negative outcomes. Yet, reducing the likelihood of negative outcomes should be an important goal of public policy. In order to generate robust policies, the sources of uncertainty in model dynamics should be considered explicitly. In this case, policy interventions need to be adaptive (see Lempert, 1999; Lempert et al., 1996; Lempert et al., 1998). This implies that in designing policies, the analyst needs not only to choose policy levers but also "sign posts" (e.g., the market share of the new technology) and response functions.

2.2 Technology Diffusion, Factors Substitution, the Labor Market and the Distribution of Income

Social interactions aside, endogenous technology diffusion also introduces sharp differences in the dynamics of macro variables. The fact that new and old technologies coexist is not new in macroeconomic modeling. Indeed, this has been the main contribution of vintage modeling in any of its flavors (putty-putty or putty-clay[1]). However, in vintage models, new investments are always allocated to new technologies (see Meijers, 1994 for a departure from

this approach). The implication is that as soon as a new efficient technology enters the market, new investors adopt it. Old investors will follow as soon as the optimal scrapping date of their technology is reached. This is in contrast to the overwhelming evidence that the adoption of new technologies is a gradual process.

The model that I introduced in Chapter 5 departed from the vintage tradition by formalizing the process through which agents learn about the characteristics of new technologies as well as the uncertain dynamics of the economic environment. The computational experiments of Chapter 5 showed high variance in the dynamics of the market share of the new technology. This variance increased with time. While in some cases the new technology was able to capture high market shares, in others, it was unable to diffuse. This phenomenon reflects the existence of network externalities that are the source of the uncertainty surrounding the dynamics of the market share of new technologies. In other words, the uncertainty surrounding the diffusion of new technologies lies not only in the distribution of the parameters that characterize the technology (e.g., costs reductions resulting from increasing number of adopters) but in the process through which heterogeneous interactive agents learn. This is the process that ultimately one needs to formalize if we want to have better representation of the technology diffusion process. Policies derived from models that ignore this process may be biased.

My treatment of technology also differs from the standard aggregate production function macro model, in that factor substitution is limited. Those promoting the development of vintage putty-clay models have for long criticized perfect factors substitution as an unrealistic assumption. In my model, once a technology has been installed, substitution between capital and labor is no longer possible. When technologies are assumed to impose constraints on the mix of labor (e.g., high vs. low quality labor), the model introduced in this research is also able to explain persistent inequality. Indeed, assume that there is full employment of high quality labor but unemployment of low quality labor. To reduce unemployment, the wage for low quality labor has to decrease. However, the only way to hire more low quality worker is to hire more high quality workers. Thus, wages for the latter need to increase. As technology incentives in high quality labor diffuse, this phenomenon

exacerbates. Thus, as predicted by other theoretical studies, technological transitions can be accompanied by an increase in income inequality. When income inequality is a policy target, policy analysis should be conducted with models that are able to formalize this phenomenon.

2.3 Identifying Model Parameters: Measuring Networks

The development of macroeconomic agent-based models is not without difficulties. Besides complexity in model dynamics, is the problem of model validation. How can we be sure that the models provide a reasonable representation of the real world? Increasing computational power allows the implementation of econometric techniques such as moments simulation methods that can be used to identify model parameters. Indeed, it is possible to search for a set of model parameters that maximize the likelihood of replicating empirical data (e.g., GDP growth rate, or labor productivity growth rate). Nonetheless, in the case of parameters characterizing networks, it is hard to assess the validity of the estimates. Indeed, the networks that I use in this research are still very stylized and cannot be directly related to real social networks. This can be even a more complex task if we think that in real life we observe several layers of networks. In other words, individuals belong to more than one network.

Thus, the challenge in constructing models with emergent macro-behavior is to improve our knowledge of the micro-economy. We need to generate a better characterization of the empirical counterpart of our networks. This task may seem daunting but it may be the best strategy to improve our understanding of how the economy operates. The alternative would be to continue to think that complex microeconomic behavior can be aggregated into the behavior of a single representative agent.

As discussed in Chapter 3, there are currently studies that measure the structural dimension of social capital. Since our focus is on developing countries, most of the current efforts should be targeted at generating maps of network structures within rural areas. These are the areas that concentrate most of the poor and where the diffusion of new technologies with

higher productivity and lower environmental damages is particularly critical. Survey instruments become the key mechanism to accomplish this goal. To proceed, countries can be divided into grids, and networks of formal and informal producers within these grids can then be studied. Longitudinal data about adoption of particular technologies (similar to the case of hybrid cocoa in Ghana), where we observe over time the adoption of given technologies by members of the networks in the different grids, could then be used to validate our models and test our theories. It is important to mention that the purpose is not to reproduce the exact network (for example in terms of number of agents and connections) within a simulation model, but to produce a reduced model of the real network that mimics its behavior. If these measurements can be undertaken for different economic sectors, we can start to generate the data required to validate multi-sector agent-based macroeconomic models.

3. Promoting and Monitoring Sustainable Growth

3.1 Indicators of Sustainable Growth: What They Show and What They Hide

This research was not intended to provide a global recipe to promote sustainable growth. Such a recipe does not exist. Each country represents a particular case, and faces specific policy problems and economic and socio-political constraints. Nonetheless, in all cases, monitoring indicators are required. Chapter 2 showed that the dynamics of the wealth of nations could be used as an indicator of countries' ability to preserve productive capacity over the long run. In a weak sense, this is what sustainable growth is all about.

An indicator that summarizes neatly the dynamics of the flows of human, natural, and produced capital is genuine savings. This measure of aggregate savings adjusts for investments in human capital and the depreciation of the stock of natural resources. Positive genuine savings suggest that a country is increasing its wealth.

However, one should be careful when evaluating sustainability on the basis of this indicator. Indeed, positive savings may be observed even if the dynamics

of the stock of natural resources is outside sustainable levels. This is because genuine savings assume that the stock of natural resources can be fully substituted by other forms of capital. Yet, as I discussed in Chapter 2, this substitution has limits when the natural resources are essential. In this research I have showed that when this is the case, an optimal consumption schedule requires stabilization of the stock of natural resources.

Nonetheless, genuine savings can be an efficient red flag. In other words, the indicator can detect paths that are definitely not sustainable. A review of the components of genuine savings in Chapter 2 revealed that in many cases countries are reducing their total wealth, thus jeopardizing their productive capacity. There are two reasons for this. First, investments in human capital and produced capital (ranging respectively between 20-25% and 2-4%) are low compared to optimal levels and have had a tendency to decrease (see next section). The second reason is high depletion rates, in particular for countries in Africa and the Middle East.

High depletion rates do not necessarily show that countries are currently outside a sustainable path (i.e., high depletion rates may be part of an optimal consumption schedule during a given period of time). However, the maximum depletion rate that a country can sustain, is given by the product of the regeneration rate times the natural resources GDP ratio[2]. In Figure 7.1, I show that for most combinations of these two parameters, a sustainable depletion rate is below 0.05 (5%). Yet, most developing countries have depletion rates above this level.

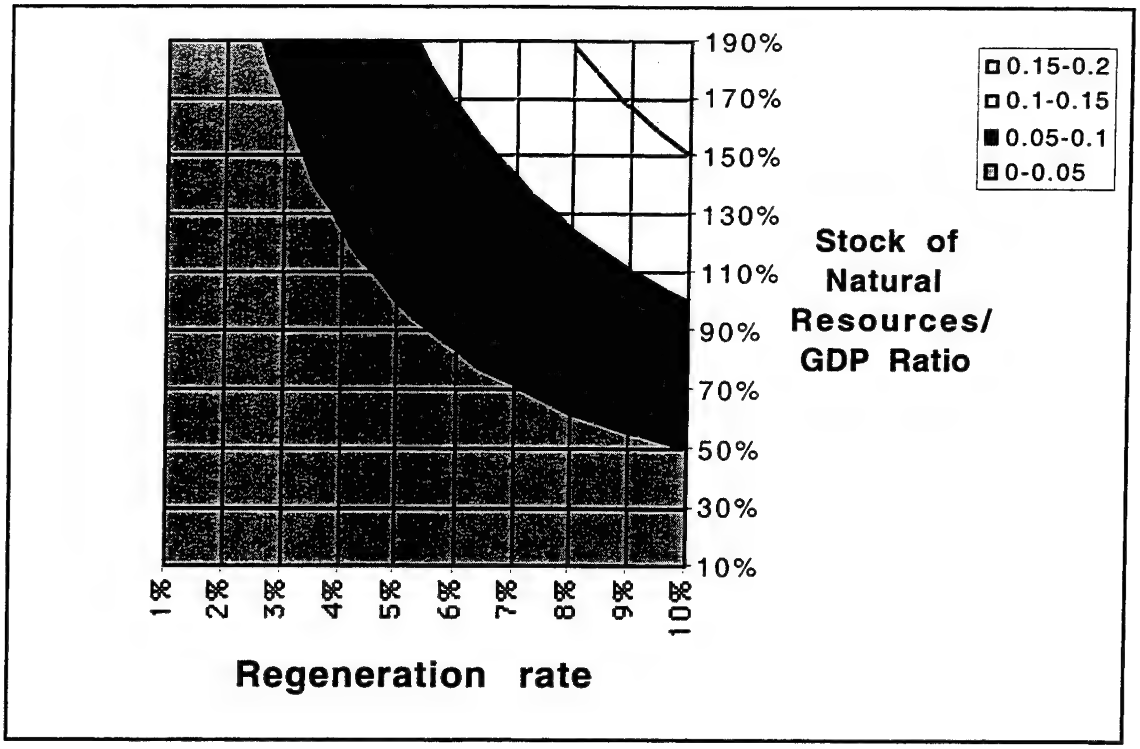

Figure 7.1: Sustainable Depletion Rates.

The econometric analysis in Chapter 2 showed that the ability of countries to reduce depletion rates depends in part on the strength of their formal institutions, as measured by civil rights and political freedom. Even after controlling for the sectorial composition of the economy, the level of economic growth and the time factor remain as key determinants of depletion rates as well. We interpreted economic development as a proxy for the level of education of the population. Time, on the other hand, can be taken as a proxy for changes in ideologies and technological innovation (i.e., new technologies become available). Hence, governments have several approaches to reduce depletion rates to sustainable levels. Nonetheless, coordination between policy instruments seems to be a necessary condition for success. For instance, efficient reductions in the carbon emission intensity of the economy requires coordination between savings, technology incentives and permits or taxes on carbon emissions. This type of coordination is likely to be necessary to address other type of environmental problems that threaten sustainable growth.

3.2 The Limits of Technological Miracles and Price Signals

Even if new production technologies are less intensive in natural resources, reductions in depletion rates will not be necessarily achieved. One reason is that, paradoxically, technological progress brings new problems by solving old ones. For example, replacing 25 million horses in the USA with cars and tractors resulted in cleaner streets and freed 40 million hectares of agricultural land (five times the area of Austria). Yet, the car brought other types of problems such as congestion and urban smog. This phenomena also applies to the case of carbon emissions. Indeed, carbon productivity has increased by 1.3% per year (less carbon is required to produce one unit of output). However, economic growth has averaged 3% per year. Thus, carbon emissions have increased in absolute terms. This implies that government will still need to intervene through, for example, taxes or permits, to stabilize the stock of natural resources, at least those that appear to be essential (e.g., land, water, clean air). As shown in Chapter 6, the effectiveness of these policy interventions and their effect on growth depend not on the type of technology available at the time of implementation, but on the economic environment and its ability to absorb new technologies.

On the other hand, environmental policies that get the price right will not be sufficient either. This is because the process of technology diffusion itself is affected by externalities. Uncertainty and social spillovers are the more pervasive. These externalities tend to deviate the diffusion of new technologies from a socially optimal path. As shown in Chapter 5 they also impose high levels of variability in the dynamics of the market share of new technologies. Therefore, an optimal stabilization program needs to consider simultaneously technology policies and environmental policies.

3.3 Summary of Policy Insights

Insight one: Governments should invest resources in the measurement of network structures.

The analysis in Chapter 6 showed that policy instruments are highly sensitive to the type of network structures. This implies that to do the "right thing", governments need to better understand the network structure of their economy. It should be a priority of national governments and international organizations to generate maps of networks, particularly in rural areas; and invest resources in understanding the effects that these networks have on behavior.

Insight two: Governments should pay more attention to the question of how much the economy should be saving. Higher saving rates may be required not only to accumulate human and produce capital, but also to stimulate productivity growth and diffusion of environmentally friendly technologies.

In Chapter 6 I showed that in a model where technological progress results from decentralized microeconomic decisions regarding the adoption of new technologies, and where these decisions respond to information received through social interactions, optimal savings rates (i.e. optimal investment in produced capital) appear to be above 30% of GDP (this ignores depletion of natural resources). This is in contrast with observed genuine savings rates that are below 25% of GDP. Even in the case of pre-Asian-crisis emerging markets, favored by flows of foreign capital, investment rates have been lower than optimal. Why? Simply because more savings does not imply more investment. The surplus of the balance of capital is equal to the deficit in the current account. Hence, foreign capital flow can increase without affecting the investments/GDP ratio, if they only increase the deficit of the current account.

If domestic savings increase but investments in produced capital remain the same, resources will be allocated to the rest of the world (i.e., increasing the surplus of the current account or reducing the deficit). Hence, *the real*

challenge is not about increasing savings, but about increasing investments. Low interest rates, political stability, unregulated markets, and public infrastructure are some of the conditions necessary to increase these investments. Once investment incentives are in place, a key policy question is how they should be financed. If domestic savings are too low, implicitly there will exist a deficit in the current account; that deficit puts pressure on the depreciation of the domestic currency. This depreciation, however, will boost exports and therefore equilibrate the current account (implicitly increasing private savings). If domestic savings are too high, the opposite will occur. This implies that governments should not try to influence the savings rate, but limit themselves to providing incentives that increase investments in produced capital while avoiding fixed exchange rate policies. Governments should also complement investments in education and health.

Insight three: Developing countries should consider delaying the implementation of policies to reduce carbon emissions taxes, and in the mean time prioritize technology incentives

Damages from carbon emissions are uncertain and will be mostly realized in the long run. In the short run there does not seem to be an economic rational to reduce carbon emissions. This is particularly true given the current challenge to cut in half the share of the poor population by year 2015.

The benefits of carbon emissions reductions will be most noticeable when damages are high, and when the growth rate of the economy has reduced its dependence on the growth rate of carbon emissions. Investing today in new technologies will reduce this dependence and will contribute to reduce abatement costs in the future.

Insight four: As a consequence of insight 3, governments should be actively involved in the technology diffusion process. Policies such as technology incentives appear as a necessary policy instrument to guarantee sustainable growth. However, they are less likely to work in economies with low levels of social capital.

My analysis has illustrated that technology incentives (here through the form of subsidies) are likely to be part of any policy intervention to promote sustainable growth and maximize intertemporal social welfare, even if governments are not sure whether a given technology is a "winner". Subsidies exploit two types of spillover effects. First, a social spillover resulting from an increase in the number of early adopters of new technologies. These users increase information flows about new technologies and facilitate further adoption. The second effect occurs at the individual level. Under the assumption that innovations are more frequent in the case of new technologies, early users of new technologies contribute to a faster growth of the average productivity of the economy.

The effectiveness of technology subsidies depends on the level of social capital. In economies with low levels of social capital subsidies can be welfare decreasing even in the presence of increasing returns to scale in the production of new technologies (i.e. subsidies will not be cost-effective). Therefore, previous to the implementation of subsidies, levels of social capital should be measured. Research is needed to determine minimum levels required for the success of policy interventions based on subsidies. It is also important to continue to investigate how social capital can be promoted.

In the model of technology diffusion and growth, subsidies were financed out of aggregate income. This implies that a way to finance technology incentives in reality are taxes on income. These taxes will certainly have an economic cost, but the benefits from the subsidy appear to compensate for the costs. Given a highly skewed distribution of income and a small share of wages in total GDP, perhaps, most of the additional resources to promote adoption of new technologies should come out of profit earnings. One possible way to do this is to impose a tax on profits (or any income related tax such as a VAT) that finances a fund for technological innovation. The resources can then be used for example to finance demonstration projects or simply support the diffusion of some types of technologies (see recommendations on institutional capacity below).

Corollarie: Governments in developing countries should consider creating a new technical body that is in charge of coordinating policies across ministries and generating new legislation.

The analysis has shown that a growth path that is sustainable and maximizes social welfare results from coordinated policy interventions at three levels: investments in human and produced capital, technology incentives, and the environment. These types of policies are usually managed by several ministries within the executive power (e.g., the ministry of industry, the ministry of social matters, and the ministry of the environment). Systematic policy coordination across ministries is, however, rarely observed. Moreover, usually, bureaucracies within these ministries lack the technical training required to design and implement complex policy changes that in most of the cases affect chaotic pieces of legislation or even the constitution. More importantly, these bureaucracies are often stakeholders in the policy issues and tend to be politically involved. This implies that it is difficult to observe impartial analysis.

An alternative is to create a technical body that depends directly on the president. Appointments within this body should not be political, except probably for the executive director. The permanent staff should be small and most of the activities should be carried out by consultants. The technical body would assume the role of a Modernization Council. It should be in charge of coordinating policy actions across ministries and different social groups and commercial power centers. The Modernization Council would not implement policy. It should be in charge of preparing the legislation that the executive power sends to the Congress. All the critical policy questions (e.g., social security reform, and sustainable development) should be coordinated through the Modernization Council.

In the case of sustainable development policy, the Modernization Council should coordinate with the Ministries of Industry and Agriculture the development of an inventory of production technologies by sector, and evaluate

the magnitude of the technological gap of each of these sectors. With the Ministries of Energy, Agriculture and the Environment, the Modernization Council should evaluate the natural resource base, identify critical environmental problems, and design appropriate technology and environmental policies. It should also advise the Ministry of Finance on the appropriate allocation of the government budget - in particular health, education and social security - and coordinate the reform of the health, education and pension systems. Several countries are moving to a government structure with an independent central bank whose fundamental role is to guarantee price stability. This implies that the Modernization Council will have little influence over monetary policy, that as we discussed in Chapter 4, may be required to stimulate investments in produced capital. Nonetheless, the Modernization Council should monitor indicators of sustainability, in particular investment rates, and coordinate policy actions intended to generate incentives for such investments and to measure their environmental impacts. Modernization of the communications, transport, and energy distribution systems are examples of the type of policy interventions that could be undertaken. The Modernization Council could also, through the Department of Statistics, be the institution that generates network maps for different regions of the country.

Because the majority of the policy analysis would be centralized by the Modernization Council, inter-sectorial constraints could be taken into account by each individual project.

To finance the series of studies that are required to design a robust development strategy, the Modernization Council should try to rely on resources from governments and international organizations. Loans to conduct the type of policy studies that I have discussed and develop legislation are often available but do not find demand.

4. Future Research

This dissertation opens several avenues for future research. A first area of research concerns the search for adaptive robust policies. This type of exercise will be also useful in identifying the type of "sign posts" that policymakers should consider when developing policies to promote sustainable growth.

A second area of research is model validation. Integrated assessment models should be considered as technologies themselves. Before models of the type developed in this research diffuse, several improvements are required. We have already discussed that we need better data on networks to be able to construct more realistic structures within our models. We also need to expand the treatment of technology adoption decisions. Here, I have worked with only two technologies. Technological progress resulted first from the adoption of the new technology (that basically increased the quantity of output per unit of natural resource), and second from the spread of random technological innovations through the network. In standard macro-vintage models new technologies (i.e., capital vintages) appear in each period of time and their productivity is exogeneously determined. It has been shown that such a method of modeling technological progress produces better results when reproducing empirical data than aggregate production function models. My claim is that even better results can be generated through models such as mine, if we increase the number of technologies that enter the market. Three sets of parameters can then be estimated econometrically to replicate observed data: those that govern the emergence of "random" technological improvements (learning by using), those that govern the improvements in the structural parameters of the new production functions (i.e., technologies) that enter the market (learning by doing); and those that define the network class and therefore implicitly the spread of technological discoveries through the network. The performance of a model such as the one described here should be evaluated in terms of its ability to reproduce real data. This ability should be evaluated in reference to standard vintage models.

A strong assumption of my model relates to the number of agents and their social organization. Regarding the number of agents, some caveats are worth mentioning. First, when modeling a given economy, it is not possible yet to have a digital representation of each producer, due to computational constraints. This implies that economies need to be scaled. In other words, the population of agents is reduced but the per capita values of the macro variables of interest are preserved. However, it is not clear which is the appropriate scaling factor in terms of social interactions. For example, if we scale by a factor of 10^4 a population of 2 million producers with an average connectivity per capita of 100 individuals, we end up with a population of 200 producers with an average of less than one connection per capita. Clearly, this new economy will not behave as the real economy since connections will be too scarce (i.e., many individuals will be completely isolated). Again, one can think about estimating econometrically the parameters that define the network in order to maximize the likelihood of reproducing the per capita value of per capita variables of interest. If this exercise is repeated in different economies or different periods of time, it may be possible to derive a relationship between the observed network connectivity and the estimated network connectivity.

In this version of my model, the number of agents and the network structure has been held fixed. This is clearly an unrealistic assumption. I believe that if we improve our understanding of the dynamics of real networks, this assumption can be relaxed. Basically, the number of agents will be growing at some empirically estimated growth rate. Then it will be necessary to have an estimate on the probability that the agent will be located in alternative regions of the network. In this research the network had a geographic and a social dimension. One can think about adding a third dimension in a way that two dimensions characterize geography and the third characterizes social position. This type of network structure can be more easily related to real networks. This brings me again to the discussion on surveys and measurement of networks. Better understanding of macro-behavior needs to start with a better understanding of micro-behavior. This should be done through measurement and analysis of individual interactions. More resources should be allocated to measure social capital and its effects on behavior. Only in this

way we will be able to close the gap that has always existed between microeconomics and macroeconomics.

Finally, it is important to move from the average-developing-country approach, to country specific applications if possible within a multiple resources framework. Policies derived from the agent-based model should be compared to policies derived from standard macro models.

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[1] The term putty (as opposed to the term clay) refers to the ability to substitute between production factors. Putty-putty models allow for factor substitution before a technology has been chosen (i.e., the choice of a given technology implicitly determines choices about the combination of inputs) and after the technology has been installed. In putty-clay models, substitution is no longer possible once the technology has been installed.

[2] The depletion rate d for country i is given by: $d_i = n_i / Q_i$ where n is the consumption of natural resources and Q is GDP. The sustainable consumption is given by: $n_i^* = R.N_i$ where R is the regeneration rate and N is the stock of natural resources. It follows that the sustainable depletion rate is $d_i = R.\eta_i$ where η is the natural resources/GDP ratio given by: $\eta_i = N_i / Q_i$.

Chapter 8 - Appendixes

Appendix 8.1. Individual Preferences for Growth, Environment, and Income Distribution

	Funds to be invested in projects that will stimulate economic growth	Funds to be invested in projects to reduce environmental damages	Funds to be invested in projects that will reduce income inequality
Average	3.85	4	2
Standard Error	1.34	1.46	0.87

Source: Author calculations.

Appendix 8.2. Composition of the Wealth of Nations (Figures in per Capita USD current)

	Population	GNP	Total Wealth	Human Capital	Produced Capital	Natural Capital
Argentina	34,180,000	8,063	199,794	168,482	13,352	17,960
Australia	17,841,400	17,982	404,903	272,244	67,193	65,466
Austria	7,914,690	25,307	364,960	272,918	77,749	14,292
Bangladesh	117,787,000	220	31,837	24,142	2,161	5,534
Belgium	10,080,400	23,001	360,777	299,137	61,625	15
Benin	5,246,000	376	36,206	28,556	4,015	3,634
Bolivia	7,237,000	770	53,924	33,906	8,980	11,038
Botswana	1,443,000	2,800	124,898	98,663	15,473	10,762
Brazil	159,143,000	3,370	125,813	96,758	15,902	13,154
Burkina Faso	10,046,000	302	20,824	14,327	2,169	4,327
Burundi	6,209,000	149	14,564	8,893	2,165	3,506
Cameroon	12,871,000	686	48,044	27,459	8,286	12,298
Canada	29,120,700	19,656	443,272	312,191	66,608	64,474
Central African Republic	3,235,000	370	33,374	17,704	3,136	12,535
Chad	6,183,000	193	23,308	11,278	1,752	10,279
Chile	14,044,000	3,507	207,640	163,084	17,203	27,353
China	1,190,920,000	530	50,757	40,297	5,989	4,471
Colombia	36,330,100	1,620	119,294	97,056	11,691	10,546
Congo	2,516,000	635	44,917	27,684	9,295	7,939
Costa Rica	3,304,000	2,400	135,499	106,588	14,635	14,277
Cote D'Ivoire (Ivory Coast)	13,780,000	N/A	31,426	18,219	6,214	6,993
Denmark	5,172,770	28,285	375,477	285,331	71,264	18,882
Dominican Republic	7,684,000	1,319	97,060	73,955	8,079	15,026
Ecuador	11,220,000	1,311	97,158	62,970	14,480	19,708
Egypt	57,556,000	700	72,236	51,883	16,246	4,106
El Salvador	5,641,000	1,478	56,951	50,186	4,675	2,090
Finland	5,082,570	18,874	315,301	194,587	90,190	30,524
France	57,726,200	23,552	381,318	296,078	70,435	14,805
Gambia, The	1,081,000	359	25,873	19,277	2,725	3,870
Germany	81,140,800	25,698	353,006	279,785	65,596	7,626
Ghana	16,944,000	422	38,022	30,718	3,921	3,383
Greece	10,408,000	7,723	182,722	142,440	30,777	9,505
Guatemala	10,322,000	1,190	72,164	62,469	6,630	3,064
Guinea-Bissau	1,050,000	239	28,580	11,733	2,351	14,496
Haiti	7,035,000	219	17,998	13,534	2,947	1,517
Honduras	5,493,000	607	49,998	35,528	8,099	6,371
India	913,600,000	320	28,364	17,098	4,366	6,900
Indonesia	189,907,000	882	86,053	65,143	7,927	12,983
Ireland	3,542,940	13,738	296,895	224,199	38,911	33,784

	Population	GNP	Total Wealth	Human Capital	Produced Capital	Natural Capital
Italy	57,154,200	19,258	323,081	250,091	67,005	5,985
Jamaica	2,496,000	1,421	64,832	38,832	20,004	5,996
Japan	124,782,000	34,680	380,290	282,326	93,768	4,196
Jordan	4,217,000	1,330	91,522	74,195	15,653	1,674
Kenya	26,017,000	250	26,971	16,536	7,168	3,267
Korea, Republic of	44,563,000	8,200	224,826	192,908	26,702	5,216
Lesotho	1,996,000	681	39,414	32,849	4,805	1,760
Madagascar	13,101,000	230	24,476	11,222	1,392	11,862
Malawi	10,843,000	123	10,236	6,612	2,068	1,556
Malaysia	19,498,000	3,551	193,048	149,510	24,729	18,809
Mali	9,524,000	250	18,755	7,963	1,822	8,970
Mauritania	2,217,000	480	35,666	21,700	4,280	9,686
Mauritius	1,104,000	3,212	134,514	114,065	18,209	2,240
Mexico	91,858,000	3,865	159,175	127,965	19,313	11,898
Morocco	26,488,000	1,145	76,597	63,074	9,481	4,042
Mozambique	16,613,900	84	13,083	7,939	3,100	2,043
Namibia	1,500,000	1,981	101,573	79,204	9,894	12,475
Nepal	21,360,000	196	23,074	15,488	2,379	5,207
Netherlands	15,391,200	21,955	344,549	267,504	71,066	5,979
New Zealand	3,530,930	13,048	391,725	230,660	63,208	97,857
Nicaragua	4,275,000	321	39,529	28,576	4,042	6,911
Niger	8,846,000	227	37,013	12,511	2,178	22,324
Norway	4,317,630	26,599	386,796	243,072	99,253	44,472
Pakistan	126,284,000	440	48,171	40,894	3,957	3,321
Panama	2,585,000	2,698	136,810	108,955	16,151	11,704
Papua New Guinea	4,205,000	1,158	58,205	37,470	6,445	14,291
Paraguay	4,830,000	1,556	88,379	64,939	10,268	13,172
Peru	23,331,000	1,882	84,447	61,329	14,815	8,303
Philippines	66,188,000	972	62,844	51,296	6,780	4,768
Portugal	9,831,980	9,437	226,000	184,769	33,893	7,337
Rwanda	7,750,000	80	7,781	3,740	2,010	2,030
Saudi Arabia	17,497,600	7,365	280,099	109,721	30,112	140,266
Senegal	8,102,000	622	46,578	32,838	4,016	9,724
Sierra Leone	4,587,000	144	16,403	9,373	1,558	5,472
South Africa	41,591,000	2,963	116,194	91,559	16,793	7,841
Spain	39,550,900	13,143	257,873	204,181	43,300	10,392
Sri Lanka	18,125,000	631	65,273	51,309	7,806	6,158
Sweden	8,735,350	23,753	334,488	237,074	69,638	27,777
Switzerland	7,126,850	36,487	441,132	324,347	111,166	5,620
Tanzania	28,846,000	90	12,762	4,388	4,170	4,205
Thailand	58,718,000	2,382	163,446	133,349	16,658	13,439
Togo	4,010,000	320	25,854	17,457	3,613	4,784
Trinidad and Tobago	1,292,000	3,749	174,291	120,607	38,537	15,147

	Population	GNP	Total Wealth	Human Capital	Produced Capital	Natural Capital
Tunisia	8,815,300	1,790	114,292	86,679	16,584	11,029
Turkey	60,771,000	2,453	109,396	91,014	11,329	7,052
Uganda	18,592,000	200	22,911	13,315	5,633	3,963
United Kingdom	58,087,600	18,507	338,466	278,536	51,253	8,677
United States	260,529,000	25,872	524,887	419,396	76,468	29,023
Uruguay	3,167,000	4,644	174,046	133,121	13,377	27,548
Venezuela	21,378,000	2,734	165,234	93,114	31,759	40,362
Viet Nam	72,500,000	189	26,336	17,572	1,719	7,044
Zambia	9,196,000	350	22,388	8,802	3,582	10,004
Zimbabwe	11,002,000	480	43,236	28,784	9,743	4,708

Appendix 8.3. Introduction to the Random Field Two Dimensional Estimator

This Appendix has been reproduced with minor notational changes from Quah (1992). Define the distance between two points z_1 and z_2 in Z_, where $z_1 = (j_1, t_1)$ and $z_2 = (j_2, t_2)$ as:

$$\|z_1 - z_2\| = \max\left(|j_1 - j_2|, |t_1 - t_2|\right).$$

Similarly, the distance between any two subsets A_1 and A_2 in Z_ is

$$d(A_1, A_2) \overset{def}{=} \inf_{\substack{z_1 \in A_1 \\ z_2 \in A_2}} \|z_1 - z_2\|.$$

Fix a probability space (Ω, F, Pr). For $p > 0$, denote the p-norm of a random variable (rv) X on $(\Omega, F, \Pr)$ by $\|X\|_p \overset{def}{=} E^{1/p}|X|^p = \left(\int_\Omega |X(\omega)|^p \, d\Pr(\Omega)\right)^{1/p}$. As usual, if $G \subset F$ is an σ-algebra, then $X \in G$ indicates that X is G-measurable.

Definition 7.1: A random field is a collection of rv's $\{u_z \mid z \in Z^2\}$ on $(\Omega, F, \Pr)$.

For F_1 and F_2 two sub-σ-algebra of F, define the α-mixing coefficient

$$\alpha(F_1, F_2) \overset{def}{=} \sup_{\substack{F_1 \in F_1 \\ F_2 \in F_2}} |\Pr(F_1 \cap F_2) - \Pr(F_1).\Pr(F_2)|,$$

and the symmetric ϕ-mixing coefficient

$$\phi^s(F_1, F_2) \overset{def}{=} \sup\left(|\Pr(F_1/F_2) - \Pr(F_1)| \vee |\Pr(F_2/F_1) - \Pr(F_2)|\right),$$

where the sup in ϕ^s is taken over F_1 in F_1 and F_2 in F_2 such that $\Pr(F_1) > 0$ and $\Pr(F_2) > 0$. The s superscript (denoting *symmetric*) distinguishes ϕ^s from the usual ϕ-mixing coefficient.

Both α and ϕ^s quantify dependence between two σ-algebra of events: α and ϕ^s equal zero whenever F_1 and F_2 are independent.

For $A \subset Z^2$, let $S(A)$ be the σ-algebra of events generated by $\{u_z \mid z \text{ in } A\}$. For $m \geq 1$, and A1 and A2 subsets of Z^2, define the sequences:

$$\alpha_m \overset{def}{=} \sup_{d(A_1,A_2)\geq m} \alpha(S(A_1),S(A_2)),$$

$$\phi_m^s \overset{def}{=} \sup_{d(A_1,A_2)\geq m} \phi^s(S(A_1),S(A_2)) .$$

Using the same symbols α and ϕ^s is without loss of clarity. It is straightforward now to extend the usual time series discussion to random fields. The random field u_z is α-mixing (ϕ^s-mixing) if $\alpha_m \to 0 (\phi_m^s \to 0)$ as $m \to \infty$. The sequence α_m is of size -q if $\alpha_m = O(m^\lambda)$ for some $\lambda < -q$, so that $\sum_m \alpha_m^{1/q} < \infty$; similarly for the sequence ϕ_m^s. The smaller (algebraically) is the size, the faster is the sequence of mixing coefficients required to vanish. It is easy to see that ϕ^s dominates α, so that ϕ^s mixing implies α mixing.

The sequences α and ϕ^s above are natural counterparts of the usual mixing coefficients in time series econometrics: they specialize appropriately when the index set is restricted to be one-dimensional, and A_1 and A_2 in the definitions are half-lines.
Sharp probability inequalities are the basis for useful consistency and asymptotic distribution results. For random fields, the following Hölder-related inequalities, already familiar in the time series applications, are immediate from probability theory:

LEMMA 7.2: Let A_1 and A_2 be subsets of Z^2, and let $X_1 \in S(A_1)$ and $X_2 \in S(A_2)$. For p and q real numbers such that p>1,

(i) if $p^{-1} + q^{-1} < 1$, then

$$|EX_1X_2 - EX_1X_2| \leq 15\alpha(S(A_1),S(A_2))^{1-p^{-1}-q^{-1}} \|X_1\|_p \cdot \|X_2\|_q .$$

(ii) if $p^{-1} + q^{-1} = 1$, then

$$|EX_1X_2 - EX_1X_2| \leq 2\phi^s(S(A_1),S(A_2))\|X_1\|_p \cdot \|X_2\|_q .$$

The first result is also known as Davydov's inequality. It is convenient to give slightly different regularity conditions for different results.

Assumption A0: Let $\{u_{jt}, j = 1,2,....,N; t = 1,2,....,T = kN\}$, with k a fixed positive number, be (part of) a random field. Assume $Eu_{jt} = 0$ for all j and t.

This assumption builds in the restriction that the time and cross-section dimensions are of the same order of magnitude; the zero mean property will be guaranteed under the hypothesis of interest.

Assumption A1: The random field $\{u_{jt}\}$ is α-mixing, and for some r > 2, (a.) $\sup_{jt}\|u_{jt}\|_r < \infty$ and (b.) $\sup_{jT}\left\|T^{-1/2}\sum_{t=1}^{T} u_{jt}\right\| < \infty$.

Requiring mixing rules out common factors and "fixed effects".

Suppose that in **A1**, we require the α-mixing sequence to have size -r / (r -2) and further assume $\lim_{t\to\infty} Var\left(T^{-1/2}\sum_{t=1}^{T} u_{jt}\right) > 0$. Then for each fixed j, as $T \to \infty$, the quantity $T^{-1/2}\sum_{t=1}^{T} u_{jt}$ converges in distribution to a non-degenerate normal rv. The limiting rv then has moments of all orders. In fact, for each j, $(T^{-1/2}\sum_{t=1}^{T} u_{jt})^2$ is uniformly integrable in *T*. Uniform integrability holds across j as well, under this stronger mixing assumption. Part (b.) of **A1** strengthens this conclusion by requiring a uniform bound on the r-th absolute moment for all T and j. Alternatively, notice that if u_{jt} were normally distributed to begin, then the normalized partial sum $T^{-1/2}\sum_{t=1}^{T} u_{jt}$ is again normally distributed, and so would have finite absolute moments of all orders.

At times, it will be necessary to use stronger conditions than provided in **A1**.
These are given in the following.

Assumption A2: For some r > 2, $\sup_{j,t}\|u_{jt}\|_r < \infty$ and $\{u_{jt}\}$ is mixing with either ϕ^s coefficients of size -2 or α coefficients of size -2r/ (r - 2).

Assumption A3: The field $\{u_{jt}\}$ obeys: (a.) for some r > 4,

$$\sup_{j,T}\left\|T^{-1/2}\sum_{t=1}^{T} u_{jt}\right\|_r < \infty$$

and $\{u_{jt}\}$ is mixing with either ϕ^s coefficients of size -r/2 (r - 2) or α coefficients of size -r/ (r - 4), and (b.) the sequence of variances

$$v_N^2 \stackrel{def}{=} Var\left(N^{-1/2}\sum_{j=1}^{N}(T^{-1/2}\sum_{t=1}^{T} u_{jt})^2\right)$$

satisfies $\lim_{N\to\infty} v_N^2 > 0$.

Assumptions **A2** and **A3** strengthen **A1** in different ways. Both impose an explicit size requirement on the mixing coefficients whereas in **A1** the mixing coefficients are only assumed to tend to zero. In **A2** and **A3**, the decay rate is explicitly linked to the existence of different higher order moments. As usual, the slower is the decay rate, the greater is the number of higher order moments that are required to be finite. Condition (b.) of **A3** is equivalent to a bound on the information matrix in likelihood-based models, and is standard.

The assumptions above will typically be sufficient for consistent estimation. For inference, we will impose:

Assumption A4: The random field $\{u_{jt}\}$ is such that (a.) for some r > 4,

$$\sup_{j,t}\|u_{jt}\|_r < \infty, \quad \sup_{j,T}\left\|T^{-1/2}\sum_{t=1}^{T} u_{jt}\right\|_r < \infty,$$

and $\{u_{jt}\}$ is mixing with either ϕ^2 coefficients of size -2 or α coefficients of size -2r/ (r - 4), and (b.) as in **A3**.

Notice that assumption **A4** implies **A1**, **A2**, and **A3** because for r > 4, we have -2r/ (r - 4) ≤ min (-r/ (r - 4), -2r/ (r - 2)) and -2 ≤ -1 ≤ -r/ 2 (r - 2).

Our first result will be useful for the consistency proofs below.

Let $\{X_{jt}\}$, with N ≥1, $j = 1,2,\ldots,N$, and $t = 0,1,\ldots,T = kN$ be observed data. Define the field data regression coefficient of X_{jt} on $X_{j,t-1}$ as:

$$\beta_N \overset{def}{=} \left(\sum_{j=1}^{N}\sum_{t=1}^{T} X_{j,t-1}^2\right)^{1}\left(\sum_{j=1}^{N}\sum_{t=1}^{T} X_{jt}X_{j,t-1}\right)$$

field data regression distinguishes this from time series (N = 1) and panel data (T small and fixed) regressions.

The first main result is a consistency proposition for field data regression with unit roots.

Theorem 7.11: Suppose $\{X_{jt}\}$ is generated by:

(i) $X_{jt} = \beta_0 X_{j,t-1} + u_{jt}$, $j = 1,\ldots,N, t \geq 1;$

(ii) $\beta_0 = 1;$

(iii) $\sup_{j\geq 1}\|X_{j0}\|_2 < \infty;$

(iv) $\{u_{jt}\}$ satisfies **A0** and **A1**;

(v) $\inf_{j,T} T^{-1}\sum_{t=1}^{T} Var\left(T^{-1/2}\sum_{s=1}^{t} u_{js}\right) > 0.$

Then $\beta_N \xrightarrow{\Pr} 1$ as $N \to \infty$.

The consistency result above is similar to that for time series regression with unit roots (see for example Phillips, 1987). However, whereas the asymptotic distribution for the least squares regression coefficient with the time series data is non-normal, that for β_N here, appropriately standardized, is normal.

The proof of this theorem is rather long, and the reader is referred to Quah (1992, Section 9).

Appendix 8.4. Basic Mathematics for the Analysis of the Linkage Between Social Capital and Technology Diffusion: Gibbs States and Markov Random Fields

In this Appendix, I introduce briefly the concepts of Gibbs states and Markov fields respectively developed by Gibbs (1902) and Dobrushin (1968). For a more complete introduction to these concepts I refer the readers to Preston (1974), and Kemeny et al. (1966). The main application of these tools is to characterize the probability of observing different configurations or states of a system/model determined by a finite set of interconnected agents.

Basic definitions

Field of sets: Consider the set Λ for which the elements are in this case economic agents. We define the field $\mathcal{F}(\Lambda)$ as the set of subsets of Λ. Hence $\mathcal{F}(\Lambda)$ can be viewed as all the combinations of agents in Λ.

Configurations and size: Let's define $A \in \mathcal{F}(\Lambda)$ as one of the combinations in $\mathcal{F}(\Lambda)$ such that all agents in A are in some state +w (e.g., informed or using a technology 1) while the agents in $\Lambda - A$ are in some state -w uniformed or not using technology 1). We say that A represents a configuration of the system or some state of the system and refer to its size by its number of elements denoted $|A|$.

Graph: To add structure to the set of agents Λ, we introduce the concept of graph. A graph G(V,E) is constituted by a set of vertices V (points that in this case represent agents) and a set of edges E (lines that join some of the agents). Most models work with the assumption that $V \subseteq Z^2$. We say that two agents represented by vector i and j ∈ V are connected if (i,j) ∈ E. We also say that two agents that are connected are neighbors. In our application, we associate the set Λ with the graph $\mathcal{G}(\Lambda,e)$.

Boundary: Let's define:

$$c:\Lambda\times\Lambda\to\{0,1\}$$

$$c(i,j)=\begin{cases}1 & if\ \ (i,j)\in e,\\ 0 & otherwise\end{cases}$$

We define the boundary of A by the set

$\overline{A}=\left\{j\in\Lambda-A;\ c(i,j)=1\ \ for\ \ some\ \ i\in A\right\}$. Hence, the boundary of A is the set of all agents connected to some agent in A.

Simplex: We define a simplex by the set $B=\left\{i,j;\ c(i,j)=1,\ \ i\neq j\right\}$. This is a set of all the interconnected agents.

Probability measure and probability space: We define a probability measure as a function $\mu:\mathcal{F}(\Lambda)\to\Re$ such that $\mu(A)\geq 0,\ \forall A$ and $\sum_{A\subset\Lambda}\mu(A)=1$. We define the set $\wp(\Lambda)$ as the set of all probability measures μ, and call this set the probability space.

Potential: We call potential a function $V:\mathcal{F}(\Lambda)\to\Re$ such that $V(\varnothing)=0$

Gibbs state potential: We call Gibbs state potential or the potential of a state A the function:

$$\pi(A)=\left(\sum_{B\subset\Lambda}\exp V(B)\right).\exp V(A).$$

Proposition 1: The probability measure μ is a Gibbs state potential with potential

$$V(A)=\log\left[\frac{\mu(A)}{\mu(\varnothing)}\right],$$

Proof: Given V(A) and the definition of potential we have:

$$\pi(A)=\left[\sum_{B\subset\Lambda}\exp V(B)\right]^{-1}.\exp V(A)=\left[\sum_{B\subset\Lambda}\frac{u(B)}{\mu(\varnothing)}\right]^{-1}.\frac{u(A)}{\mu(\varnothing)}=\mu(\varnothing)\frac{u(A)}{\mu(\varnothing)}=\mu(A).$$ CQFD.

Interaction Potential: We define an interaction potential as the function $J_V : \mathcal{F}(\Lambda) \to \Re$ such that $J_V(A) = \sum_{X \subset A} (-1)^{|A-X|} V(X)$

Nearest Neighborhood Potential: A potential V is called a nearest neighborhood potential if $J_V(A) \neq 0$ only if A is simplex of the graph.

Nearest Neighborhood State: We say that $\mu \in \wp(\Lambda)$ is a nearest neighborhood state if $\mu(A)>0$ for all A and, given $i \neq A$ we have: $\frac{\mu(A \cup i)}{\mu(A)} = \frac{\mu((A \cap \bar{i}) \cup i)}{\mu(A \cap \bar{i})}$.

This states that the conditional probability of observing agent i in state +w given that agents in A are in +w only depends on what happens in the neighborhood of i.

Theorem A1: (Preston, 1974). If $\mu \in \wp(\Lambda)$ is a nearest neighborhood state t $\mu \in \wp(\Lambda)$ is a Markov random field.

Appendix 8.5. Proofs of Propositions 1,2, and 3, in Section 5

Proof of proposition 1

The proof of this proposition is trivial. Let's define $k^* = \max_k f(k_i) = \dfrac{f_1(k_i) - f_{-1}(k_i)}{k_i}$. Then it is possible to find c_1, c_{-1} such that $k^* > \dfrac{c_1 - c_{-1}}{p}$. Because k* is a maximum we know that f'<0 if k>k* and f'>0 if k<k*. Then we can find $k_{\min} < k^*$ such that $f(k_{\min}) \le \dfrac{c_1 - c_{-1}}{p}$ $k_{\max} > k^*$ and $f(k_{\max}) \le \dfrac{c_1 - c_{-1}}{p}$.

Proof of proposition 2

First, observe that for each agent i there is a function $\varphi(\ )$ that gives the minimum of number of connections with users of technology 1 that are required to choose that technology given the number of connections of users of technology -1, and the level of spillover effects of each connection:

$$\sum_{j \in v_1(i)} J^*_{ij} w_{-1} = \varphi_i \left(\sum_{j \in v_{-1}(i)} J_{ij} w_{-1} \right), \tag{8.1}$$

Then, I need to prove that I can construct at least one type of each typologies. I construct a typology of type ξ (the construction of a typology in ξ' is identical). Define $S_{\bar{k}(n)}; \bar{k} = k_{\max} + n\varepsilon$ as the set of agents such that $k_{\max} < k_i < \bar{k}$. Set n=1 and for each element i of $S_{\bar{k}(1)}$ create a sub-set of neighbors $\hat{v}(i) = \{ j \ne i \mid (j,i) \in E, k_j \le \bar{k} \}$ and a sub-set $\breve{v}(i) = \{ j \ne i \mid (j,i) \in E, k_j > \bar{k} \}$ such that $\hat{v}(i) \cup \breve{v}(i) = v(i)$ and restriction (8.1) holds. Repeat for all n such that $\bar{k}(n) \le K$. The resulting typology ensures that the high productivity technology will dominate the market. Indeed, at time t=1 the agents in $S_{\varepsilon\bar{k}}$ observe their neighbors. Because of restriction

(8.1) they all switch to technology 1. But then, diring the next time period, the agents in $S_{\varepsilon\bar{k}(2)}$ switch to technology 1. The process continues until all agents switch. CQFD.

Proof of Proposition 3

Proof of Proposition 3 is given in the text.

Proof of Proposition 4

Now let's prove that for a set of agents S'∈S(-1,t) we can find a process $\phi()$ that will generate connections that guarantee that S(1,t)=S(1,t-1) U S'. We need to prove that for each agent in **I**, the probability of observing connections that verify (3.25) is positive. We first observe that the probability that a given agent in S' will have $\hbar$ connections with members of S(1) is given by:

$$\Pr\left(\psi_i \in \Psi_{N_c}^k\right) = \sum_{x=1}^{\left|\Psi_{N_c}^k\right|}\left\{\prod_j \phi\left(-\beta\|i-j\|\right).\prod_z\left[1-\phi\left(-\beta\|i-z\|\right)\right]\right\}; \forall j \in J^x \wedge z \in Z^x, \qquad (8.2)$$

where ψ_i is a 1 by N_c vector that characterizes the set of connections of agent i, $\Psi_{N_C}^k$ is the set of possible connection states where k agents are connected and $N_c - k$ agents are not connected, J^x is the set of agents that are connected in permutation x within $\Psi_{N_C}^k$, and Z^x is the set of agents that are not connected in the same permutation. This probability is clearly positive, and increases with $|S(1,t)|$ and decreases with β.

On the other hand, the probability that an agent in S' is connected with an agent in S'US(-1,t) is given by:

$$\Pr\left(\psi_i \in \Psi_{N_c}^k\right) = \sum_{x=1}^{\left|\Psi_{N_c}^k\right|}\left\{\prod_j \phi\left(-\beta\|i-j\|\right).\prod_z\left[1-\phi\left(-\beta\|i-z\|\right)\right]\right\}; \forall j \in J^x \wedge z \in Z^x, \qquad (8.3)$$

This probability is also positive and increases with $|S(1,t)|$ and β.

Finally, the probability that the connections of agent i are such that they promote switching is given by:

$$\Pr(i \in S' \to 1) = \frac{\sum_{\iota \in I'_i} \Pr\left(\psi_i \in \Psi^{y_\iota}_{|S(1,t)|}\right) \Pr\left(\psi_i \in \Psi^{x_\iota}_{|S(-1,t) \cup S'|}\right)}{\sum_{\iota \in I_i} \Pr\left(\psi_i \in \Psi^{y_\iota}_{|S(1,t)|}\right) \Pr\left(\psi_i \in \Psi^{x_\iota}_{|S(-1,t) \cup S'|}\right)}, \tag{8.4}$$

This probability is also positive, and is inverted U-shapped in β. The same exercise can be performed for S(1,t+n).

By the same token, we can prove that there are neighborhoods of S(1,t) for which existing connections force them to never switch. The resulting function is U-shapped in β.

Proof of Proposition 5

Proposition 5 follows directly from Proposition 4.

Appendix 8.6. Dynamics of Fossil Fuel Depletion Rates

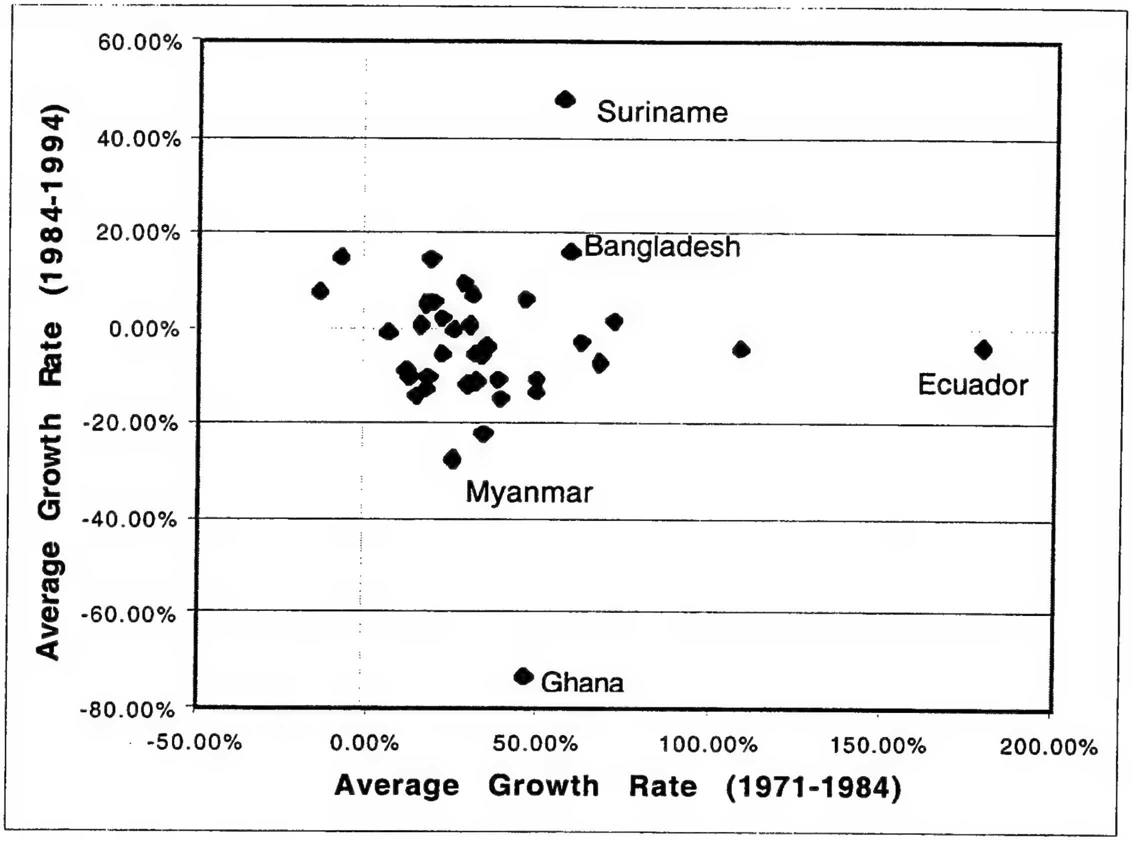
A: Depletion Rates (Rents/GNP)

Country	1970	1971	1972	1973	1974	1975	1976	1977	1978	1979
ALGERIA	6.81%	7.28%	8.09%	7.33%	24.71%	18.80%	20.12%	19.98%	16.65%	32.92%
ARGENTINA	0.44%	0.53%	0.58%	0.40%	1.30%	1.44%	1.73%	1.82%	1.74%	5.59%
BAHRAIN	..	..	..	..	..	..	..	..	..	..
BANGLADESH	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.01%	0.00%	0.01%
BARBADOS	0.01%	0.00%	0.00%	0.00%	0.15%	0.24%	0.29%	0.24%	0.45%	1.08%
BENIN	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
BOLIVIA	0.74%	1.27%	1.43%	1.71%	5.84%	4.00%	4.06%	3.42%	2.83%	7.85%
BRAZIL	0.19%	0.21%	0.17%	0.14%	0.50%	0.51%	0.47%	0.41%	0.39%	0.80%
CAMEROON	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.10%	1.21%	7.36%
CHILE	0.17%	0.16%	0.14%	0.17%	0.52%	0.92%	0.68%	0.49%	0.35%	0.86%
CHINA	0.41%	1.25%	0.87%	1.43%	6.08%	10.34%	12.49%	12.21%	15.21%	19.63%
COLOMBIA	1.32%	1.70%	1.53%	1.41%	5.29%	4.74%	4.24%	3.38%	2.68%	4.85%
CONGO	0.06%	0.04%	0.90%	4.90%	22.12%	10.52%	13.93%	13.33%	16.11%	42.12%
COTE D'IVOIRE	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.01%	0.34%
ECUADOR	0.08%	0.12%	2.53%	5.93%	18.45%	12.80%	13.62%	11.52%	11.01%	24.01%
EGYPT	1.90%	2.00%	1.45%	1.16%	4.51%	4.90%	6.84%	9.79%	9.60%	25.17%
GABON	14.39%	16.35%	16.99%	13.66%	36.52%	23.99%	19.80%	22.81%	25.27%	64.49%
GHANA	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.09%	0.37%
GUATEMALA	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.01%	0.04%	0.22%
INDIA	0.56%	0.75%	0.66%	0.77%	1.81%	3.54%	3.82%	3.35%	2.97%	3.75%
INDONESIA	5.12%	5.95%	6.96%	6.65%	17.59%	12.97%	13.52%	13.34%	11.41%	28.54%
IRAN, ISLAMIC REPUBLIC OF	..	..	..	..	54.16%	40.77%	38.45%	33.40%	25.86%	40.94%
KOREA, REPUBLIC OF	0.09%	0.31%	0.17%	0.33%	0.84%	2.05%	1.49%	1.20%	0.88%	0.65%
MALAYSIA	0.15%	0.78%	0.98%	0.73%	2.91%	3.28%	5.34%	5.46%	5.48%	13.50%
MEXICO	0.43%	0.57%	0.56%	0.56%	2.87%	2.80%	3.47%	4.89%	4.88%	10.93%
MOROCCO	0.03%	0.04%	0.03%	0.04%	0.08%	0.18%	0.19%	0.16%	0.13%	0.11%
MYANMAR	0.43%	0.53%	0.69%	0.71%	1.65%	1.70%	2.04%	2.51%	2.21%	5.15%
NIGER	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
NIGERIA	3.18%	5.83%	6.65%	7.69%	26.66%	16.05%	17.08%	16.04%	13.42%	32.21%
NORWAY	0.01%	0.02%	0.10%	0.08%	0.27%	0.90%	1.44%	1.34%	1.33%	5.98%
PERU	0.46%	0.44%	0.45%	0.45%	1.59%	1.07%	1.38%	2.13%	3.79%	11.24%
PHILIPPINES	0.00%	0.00%	0.00%	0.00%	0.00%	0.02%	0.02%	0.04%	0.03%	0.79%
PORTUGAL	0.01%	0.01%	0.01%	0.00%	0.01%	0.03%	0.02%	0.02%	0.02%	0.01%
SAUDI ARABIA	60.89%	69.25%	57.80%	31.59%	88.65%	57.00%	61.93%	65.41%	51.90%	85.08%
SOUTH AFRICA	0.36%	0.90%	0.58%	0.88%	2.13%	5.04%	6.12%	6.22%	5.38%	4.76%
SURINAME	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%	0.00%
SYRIAN ARAB REPUBLIC	2.74%	3.55%	3.59%	3.56%	9.89%	10.53%	11.04%	10.75%	9.74%	18.36%
TAIWAN, CHINA	0.07%	0.17%	0.10%	0.13%	0.29%	0.57%	0.53%	0.42%	0.32%	0.30%
THAILAND	0.01%	0.01%	0.01%	0.01%	0.02%	0.03%	0.03%	0.03%	0.02%	0.05%
TRINIDAD AND TOBAGO	9.40%	2.29%	2.48%	3.48%	34.35%	26.77%	29.15%	27.68%	23.06%	46.96%
TUNISIA	2.07%	2.49%	2.02%	1.89%	8.54%	7.20%	6.29%	6.97%	6.85%	15.77%
TURKEY	0.52%	0.58%	0.51%	0.44%	1.08%	1.06%	0.92%	0.82%	0.77%	1.12%
VENEZUELA	11.51%	14.38%	12.55%	12.42%	38.28%	25.03%	23.81%	21.66%	19.19%	42.77%
ZAMBIA	0.04%	0.14%	0.10%	0.16%	0.32%	0.89%	0.83%	0.77%	0.58%	0.46%
ZIMBABWE	0.22%	0.48%	0.23%	0.41%	0.96%	1.82%	2.82%	2.30%	2.23%	1.83%

Country	1980	1981	1982	1983	1984	1985	1986	1987	1988	1989
ALGERIA	27.84%	19.70%	15.96%	12.23%	11.61%	9.64%	3.95%	5.08%	4.21%	6.35%
ARGENTINA	6.59%	6.07%	5.02%	3.41%	2.86%	3.29%	0.38%	0.93%	0.28%	1.09%
BAHRAIN	20.96%	16.72%	14.16%	12.03%	10.91%	11.44%	7.17%	9.27%	7.04%	7.03%
BANGLADESH	0.01%	0.01%	0.01%	0.02%	0.03%	0.02%	0.01%	0.02%	0.01%	0.01%
BARBADOS	1.14%	0.66%	0.68%	0.90%	1.28%	1.21%	0.35%	0.41%	0.23%	0.25%
BENIN	0.15%	3.25%	3.08%	2.68%	3.42%	3.78%	0.85%	1.00%	0.51%	0.93%
BOLIVIA	7.58%	5.48%	6.14%	5.05%	4.74%	3.89%	0.38%	0.94%	0.30%	0.69%
BRAZIL	1.01%	1.05%	1.09%	1.67%	2.22%	2.33%	0.91%	1.09%	0.71%	0.70%
CAMEROON	9.59%	13.07%	15.34%	14.43%	18.23%	20.57%	7.09%	7.60%	5.65%	8.18%
CHILE	1.27%	1.25%	1.55%	1.48%	1.45%	1.38%	0.23%	0.31%	0.09%	0.15%
CHINA	21.02%	24.44%	23.49%	15.28%	13.20%	13.21%	8.66%	9.49%	8.00%	9.05%
COLOMBIA	5.02%	4.83%	4.40%	4.09%	4.50%	5.00%	3.85%	6.12%	4.17%	5.74%
CONGO	44.60%	44.88%	38.14%	40.46%	42.67%	39.10%	9.88%	18.06%	10.90%	18.43%
COTE D'IVOIRE	0.30%	1.02%	2.30%	3.62%	3.38%	2.77%	1.03%	1.11%	0.54%	0.22%
ECUADOR	22.65%	18.74%	19.53%	23.03%	26.02%	22.15%	10.92%	9.59%	13.41%	15.97%
EGYPT	29.29%	26.90%	24.15%	20.71%	21.36%	19.24%	4.79%	9.26%	5.13%	7.15%
GABON	48.14%	41.85%	39.95%	36.87%	33.60%	32.70%	8.04%	14.57%	6.62%	13.46%
GHANA	0.48%	0.34%	0.35%	0.32%	0.14%	0.06%	0.01%	0.00%	0.00%	0.00%
GUATEMALA	0.63%	0.56%	0.78%	0.74%	0.48%	0.34%	0.27%	0.31%	0.21%	0.24%
INDIA	3.44%	5.07%	5.40%	4.16%	4.13%	4.37%	2.71%	2.55%	2.27%	2.86%
INDONESIA	24.55%	19.73%	14.74%	14.40%	14.62%	13.51%	6.29%	8.51%	5.23%	6.22%
IRAN, ISLAMIC REPUBLIC OF	19.98%	17.59%	21.66%	16.27%	13.69%	11.69%	4.26%	10.31%	9.10%	13.73%
KOREA, REPUBLIC OF	0.87%	1.18%	1.10%	0.54%	0.41%	0.54%	0.42%	0.24%	0.20%	0.16%
MALAYSIA	13.80%	12.00%	12.09%	12.35%	12.49%	13.11%	7.35%	8.69%	6.37%	7.94%
MEXICO	12.98%	11.65%	18.79%	18.91%	15.85%	13.78%	8.30%	10.71%	6.40%	6.68%
MOROCCO	0.11%	0.21%	0.20%	0.13%	0.11%	0.15%	0.08%	0.05%	0.04%	0.04%
MYANMAR	6.42%	5.78%	4.76%	4.23%	4.51%	3.54%	1.18%	0.89%	0.44%	0.42%
NIGER	0.02%	0.05%	0.09%	0.14%	0.14%	0.20%	0.09%	0.07%	0.07%	0.10%
NIGERIA	28.45%	20.42%	17.65%	14.72%	15.87%	16.60%	14.60%	27.07%	18.48%	30.68%
NORWAY	8.09%	7.05%	6.35%	6.53%	6.86%	6.23%	2.33%	1.32%	2.49%	0.77%
PERU	10.64%	8.06%	7.33%	7.41%	7.68%	8.66%	1.73%	2.32%	2.00%	1.71%
PHILIPPINES	0.42%	0.20%	0.33%	0.43%	0.37%	0.31%	0.15%	0.13%	0.11%	0.10%
PORTUGAL	0.01%	0.02%	0.02%	0.01%	0.01%	0.01%	0.01%	0.01%	0.00%	0.00%
SAUDI ARABIA	80.88%	76.71%	56.48%	42.04%	37.58%	31.32%	27.38%	31.00%	29.30%	32.89%
SOUTH AFRICA	4.54%	7.10%	7.88%	4.16%	4.18%	7.61%	5.64%	3.16%	3.38%	3.63%
SURINAME	0.00%	0.00%	0.34%	0.34%	0.72%	1.16%	0.82%	1.18%	1.18%	4.06%
SYRIAN ARAB REPUBLIC	18.01%	15.03%	12.58%	10.91%	10.96%	10.93%	6.79%	13.98%	13.84%	21.54%
TAIWAN, CHINA	0.28%	0.28%	0.24%	0.13%	0.09%	0.09%	0.05%	0.03%	0.02%	0.02%
THAILAND	0.04%	0.07%	0.08%	0.19%	0.37%	0.59%	0.26%	0.25%	0.18%	0.21%
TRINIDAD AND TOBAGO	42.24%	31.57%	21.82%	17.82%	21.38%	20.11%	11.08%	15.28%	10.84%	15.17%
TUNISIA	16.04%	15.28%	13.71%	13.14%	12.99%	11.87%	4.80%	5.76%	3.99%	5.09%
TURKEY	1.40%	1.56%	1.63%	1.22%	1.15%	1.25%	0.77%	0.56%	0.44%	0.53%
VENEZUELA	40.17%	33.01%	27.10%	22.45%	30.57%	25.97%	12.67%	21.99%	13.78%	24.29%
ZAMBIA	0.47%	0.54%	0.68%	0.34%	0.37%	0.59%	0.79%	0.34%	0.30%	0.20%
ZIMBABWE	1.75%	1.89%	1.71%	1.27%	1.12%	1.64%	1.62%	1.32%	1.34%	1.49%

Country	1990	1991	1992	1993	1994
ALGERIA	8.53%	9.08%	8.21%	6.77%	7.63%
ARGENTINA	1.17%	0.44%	0.37%	0.13%	0.05%
BAHRAIN	9.50%	7.63%	6.66%	14.85%	13.93%
BANGLADESH	0.01%	0.01%	0.01%	0.01%	0.03%
BARBADOS	0.40%	0.31%	0.32%	0.25%	0.21%
BENIN	1.29%	0.78%	0.66%	0.41%	0.45%
BOLIVIA	1.45%	0.69%	0.57%	0.22%	0.09%
BRAZIL	0.92%	0.89%	0.92%	0.69%	0.53%
CAMEROON	10.77%	7.11%	6.94%	5.02%	6.70%
CHILE	0.22%	0.09%	0.10%	0.06%	0.04%
CHINA	10.38%	8.24%	7.15%	5.45%	3.72%
COLOMBIA	8.15%	5.91%	5.67%	4.36%	3.38%
CONGO	26.29%	16.29%	15.57%	12.47%	17.80%
COTE D'IVOIRE	0.48%	0.42%	0.39%	0.02%	0.00%
ECUADOR	20.31%	14.95%	14.50%	10.88%	10.20%
EGYPT	11.31%	8.14%	7.17%	4.26%	3.31%
GABON	22.26%	14.84%	13.90%	9.47%	11.38%
GHANA	0.00%	0.00%	0.00%	0.00%	0.00%
GUATEMALA	0.39%	0.23%	0.31%	0.24%	0.26%
INDIA	3.08%	3.15%	3.00%	2.55%	2.05%
INDONESIA	7.91%	5.45%	5.04%	3.23%	2.65%
IRAN, ISLAMIC REPUBLIC OF	20.80%	18.17%	20.09%	..	..
KOREA, REPUBLIC OF	0.12%	0.08%	0.06%	0.04%	0.03%
MALAYSIA	9.84%	7.28%	5.95%	4.72%	3.94%
MEXICO	7.55%	5.31%	4.55%	3.39%	3.11%
MOROCCO	0.04%	0.03%	0.03%	0.03%	0.02%
MYANMAR	0.41%	0.22%	0.16%	0.09%	0.07%
NIGER	0.09%	0.09%	0.09%	0.08%	0.11%
NIGERIA	39.69%	33.56%	35.16%	32.41%	23.78%
NORWAY	3.08%	0.65%	0.29%	5.16%	5.23%
PERU	2.06%	1.34%	0.92%	0.70%	0.49%
PHILIPPINES	0.12%	0.08%	0.11%	0.09%	0.04%
PORTUGAL	0.00%	0.00%	0.00%	0.00%	0.00%
SAUDI ARABIA	44.28%	41.61%	41.25%	37.67%	36.06%
SOUTH AFRICA	3.26%	2.77%	2.38%	1.87%	1.38%
SURINAME	5.61%	4.90%	7.21%	6.06%	8.48%
SYRIAN ARAB REPUBLIC	26.29%	19.47%	..	..	..
TAIWAN, CHINA	0.02%	0.01%	0.00%	0.01%	0.01%
THAILAND	0.27%	0.21%	0.18%	0.20%	0.17%
TRINIDAD AND TOBAGO	18.79%	12.43%	11.12%	8.81%	8.26%
TUNISIA	5.09%	4.33%	3.44%	2.97%	2.42%
TURKEY	0.52%	0.49%	0.45%	0.30%	0.35%
VENEZUELA	32.02%	25.58%	22.60%	18.13%	18.62%
ZAMBIA	0.24%	0.22%	0.22%	0.14%	0.01%
ZIMBABWE	1.46%	1.61%	2.01%	1.25%	0.98%

B: Changes in the Growth Rate of the Fossil Fuel Depletion Rates



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